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SHIPS LOUNGE BURNOUT EXPERIMENTS

R. C. RICHARDS AND A. DATTA

U. S. Coast Guard Research and Development Center
Avery Point Groton, Connecticut 06340

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FINAL REPORT

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NOTICE

Lloyd Breslau

L. R. BRESLAU, Ph.D.
Technical Director
U. S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340

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16. Abstract

A series of 1/4-scale and full-scale burnouts were conducted in order to examine the adequacy of the existing ship structural fire protection regulations, in light of extensive usage of modern materials. Six full-scale burnouts were conducted aboard the test vessel A.E. WATTS in typically configured and furnished crew's lounges. The lounges each had an inner and an outer room measuring 12'4" x 17'6" and 11'0" x 17'6" respectively. Marine bulkheads are rated on the basis of a standard fire test prescribed by Coast Guard regulation. The test specifies the time-temperature curve for the test furnace. The results of the full-scale tests reported show that temperatures inside the test lounge exceeded that curve within the first fifteen minutes and thereafter fell below it. The tests were also characterized by intense heat flux penetration into the bulkheads for short periods due to concentrated heat release. All of the fires were ventilation controlled. The test configuration in which air was forced into the lounge produced the most severe fires. In no case was flashover, characterized by sudden full room involvement in flames, observed. This seems to be a result of the limited ventilation during the tests.

11 FT 0 in x 17 FT 6 in

12 FT 4 in x 17 FT 6 in

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METRIC CONVERSION FACTORS

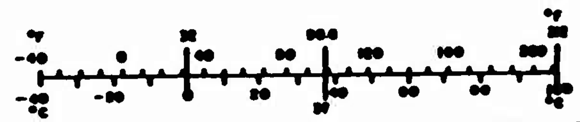
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGEMENTS

This test program was encouraged by Farrell Lines' concern for the fire safety of compartments. The Coast Guard is especially appreciative of the participation of Farrell Lines' Manager of Safety and Loss Prevention, Edward F. McIntyre. The Coast Guard is also appreciative of Johns-Manville's participation through the donation of the Marinite bulkhead material. Industry participation of this sort permits the Coast Guard to carry out an economical fire research program which is meaningful to a broad area of the maritime community.

The authors would also like to thank Clare B. Billing, Jr. for the effort he invested in preparing for and conducting Burnouts 1 and 2. His dedication to detail established an excellent base from which all of the burnouts were conducted.

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1.0 INTRODUCTION: STRUCTURAL FIRE PROTECTION FOR SHIPS COMPARTMENTS

Fire on board a ship is of major concern to mariners and passengers. If one is forced to abandon a burning ship, it is not to the safe refuge outside a building, but rather to lifeboats and the sea. Furthermore, the paths of escape are generally upward, which is the same direction that fire and smoke spread most rapidly. Despite the advent of steel ships, fires still cause unnecessary loss of life and property. For these reasons the Coast Guard promulgates a number of regulations for fire protection and containment on ships.

The basis for Coast Guard regulations can be traced to the 1930's. In 1934 the U.S. passenger vessel MORRO CASTLE burned off the coast of New Jersey within sight of bystanders on the shore. This disaster took 124 lives. A consequence of this disaster and the collision and sinking of the MOHAWK with 45 deaths was the U.S. Senate's formation of the Technical Committee on Safety at Sea. This committee was first convened on 17 June 1935 and charged with preparing among other things "a comprehensive set of rules for the construction of all classes of new vessels concerning ... fire-resisting qualities ..." A Subcommittee on Fire Control was formed to investigate the fire hazard. This subcommittee was responsible for devising and supervising the fire tests on the steamship NANTASKET[1] conducted in the first half of 1936.

1.1 NANTASKET Fire Tests

The Subcommittee on Fire Control proceeded on the assumption that "the most foolproof solution to the problem would be construction of such a nature that it would confine any fire to the enclosure in which it originated." To explore techniques for implementing this, the SS NANTASKET was obtained from the James River, Virginia, reserve fleet. She was of steel construction and her bridge enclosure was chosen for the fire tests. Staterooms were constructed of impregnated wood, untreated wood, asbestos compositions, and steel in this enclosure. A temperature in each stateroom was obtained by averaging six thermocouples. Five of these were suspended one foot below the ceiling, one in each corner of the room, and one in the center. The sixth was four feet below the ceiling and in the center.

A preliminary test was conducted in a room outfitted as a typical stateroom would be. Ignition was started with a cigarette in the bedclothing and aided by a small amount of coal oil. The fire "gave reason to believe that the severity of such a stateroom fire as might occur under ordinary conditions could very nearly equal the severity of fire represented by the standard reference time-temperature curve used in test laboratories." This curve, hereafter referred to as the "standard curve", is the standard time-temperature curve found in ASTM E119, Standard Methods of Fire Tests of Building Construction and Materials. Cord wood and kindling were used as the fuel in the remaining tests because of convenience and economy. Approximately five pounds of wood per square foot of floor area was used to simulate the fuel loading of furnishings and passenger effects.

The subcommittee reported that the tests conclusively demonstrated that it is possible to construct from commercially available materials enclosures of such integrity that a fire consuming the entire combustible contents

would be confined to the compartment of origin. Thus construction that was both noncombustible and capable of resisting the passage of fire for a limited time was introduced. Further, it was promoted by the maritime community[2] and a Congressional investigatory committee.[3] The latter recommended that "Within the main vertical zones, where the steel bulkheads covered by section 724 are not required, the bulkheads in staterooms and similar enclosures shall be of panel construction of incombustible material which will remain intact in case of a conflagration and the Bureau's rules and regulations shall prescribe tests for determining the insulating quality and suitability of the material and construction used." The "Bureau" referred to in this passage is the Bureau of Marine Inspection and Navigation, whose regulatory functions were later taken over by the U.S. Coast Guard. The tests that evolved were based on the "standard reference time-temperature curve" which is still used in Coast Guard regulations and defined in appendix I of ASTM Standard E119, "Fire Tests of Building Construction and Materials."

1.2 Stateroom Fire Test

In the late 1940's the thought occurred that ship construction of the day was being unduly penalized by requiring the construction to withstand the "standard curve." The argument was that combustible trim and veneers were eliminated from new construction and that metal furniture was being used to a large extent. This reduction in the fire load of compartments raised the question of whether the standard curve temperatures could be reached if a normally occupied stateroom were consumed by fire. A theory was also being promoted at the time that bare aluminum would conduct and dissipate heat and thus reduce structural damage caused by the fire. To examine these points, a test program was initiated jointly by the U.S. Coast Guard and Gibbs and Cox, Inc. It was conducted by the National Bureau of Standards in their Wall Testing Building and reported as the "Stateroom Fire Test" to the Society of Naval Architects and Marine Engineers in 1950.[4]

The Stateroom Fire Test was designed to demonstrate whether or not the burning of all the combustibles in the space would result in temperatures similar to those indicated by the standard curve. It simulated severe fuel-loading conditions in an interior stateroom for tourist-class accommodations of three persons. The stateroom was 11 ft 6 in. by 9 ft with an 8-ft ceiling height and a simulated deck-to-deck spacing of 9 ft 3 in. Reflected rooms were constructed on three sides and a simulated passageway occupied the fourth. The bulkheads were constructed of 3/16-inch aluminum with stiffeners and the decks were 7/16-inch aluminum supported by steel beams. The stateroom was outfitted with furnishings and personal effects for three, providing a total fuel load of approximtely 4,300,000 BTU. Ventilation was provided through a ceiling fixture (approximately 180 cu ft per min) and by an open door. The fire was started by an ignitor in a wastebasket partially filled with gift wrappings.

After observing an oxygen-controlled fire in the early stages, the test personnel removed a gypsum panel which was covering the upper portion of the door trunk. From this point on, the fire was very active until it was terminated at 55 minutes. A graph of the average of five thermocouple readings from this test is reproduced in figure 1. The time-temperature history has been time-shifted to compensate for the delay prior to free burning in the

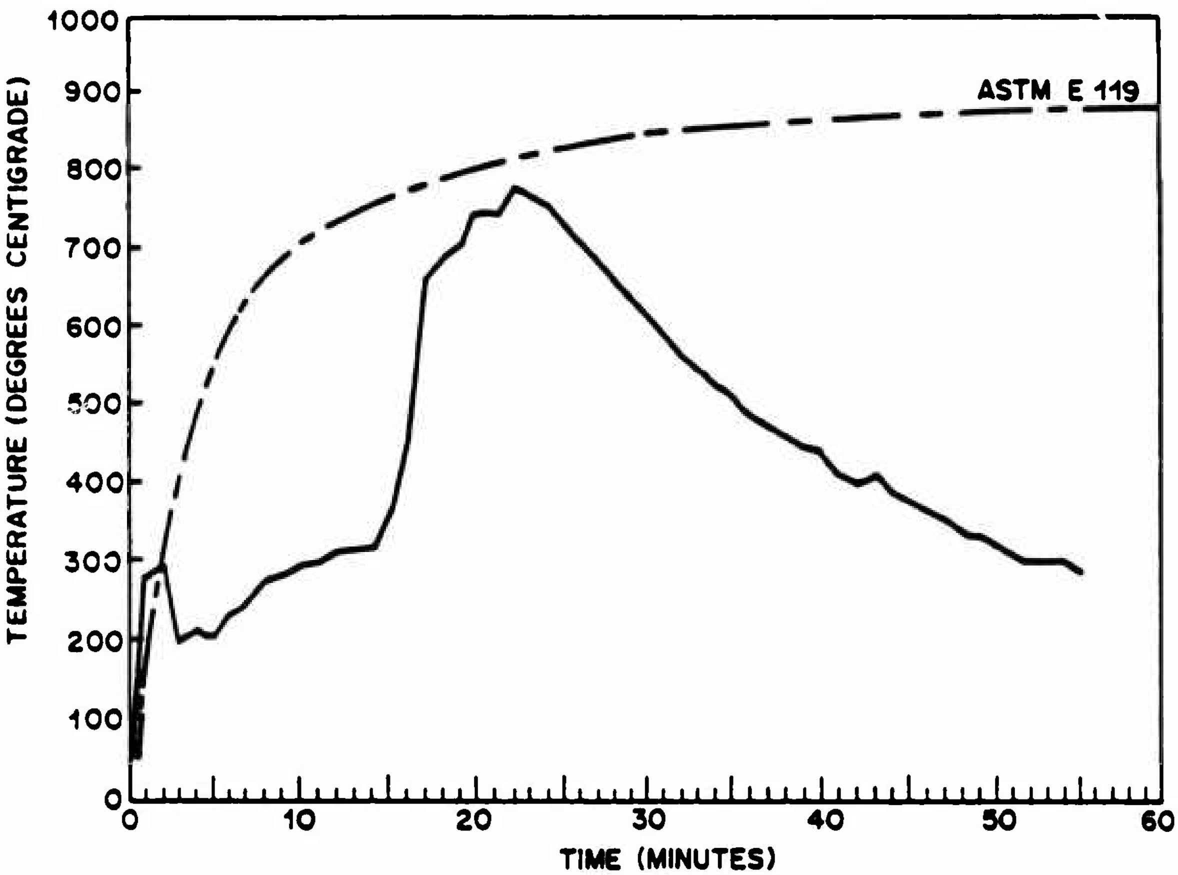


FIGURE 1. Stateroom Fire Test; Composite (Five Thermocouples) Temperature History

compartment. The authors concluded that in view of the temperature measurements and in the interest of providing a factor of safety against unusual conditions, the adherence to the then-current testing standards which employed the standard curve should be continued.

1.3 Cabin Burnout Test

A few years later the British Ministry of Transport conducted a series of bulkhead tests and a "Cabin Burnout Test" as reported in 1953.[5] The objective of the Cabin Burnout Test was to assess the protection afforded by insulation to aluminum structures in an actual fire, and to ascertain how these results were related to the standard curve.

The test cabin nad two berths and an overall floor area of 80 square feet. The ceiling height was 8 feet. No attempt was made to restrict the amount of combustible material, and it was believed that the amount of combustibles per cubic foot of volume represented the maximum obtainable in any ship. The furniture was painted wood, foam rubber mattresses were fitted to the bunks, bedding was made up on the mattresses and an allowance for the passengers' personal effects was included. This gave a total fuel load of 4,914,700 Btu and thus the average fuel load of 61,434 Btu per sq ft as compared to 41,546 Btu per sq ft for the Stateroom Fire Test and approximately 41,000 Btu per sq ft for the NANTASKET tests.

Ventilation was more than adequate for the test. It was provided by natural convection through the cabin door left ajar, a 10-inch diameter side scuttle left open and an open 8-inch square vent in the overhead. The fire was lit by dropping a lighted torch into a wastepaper basket filled with crumpled paper. Ventilation was enhanced at the point where oxygen starvation was beginning to set in by the collapse of one of the panels (at approximately 15 minutes). Examination of the thermocouple readings showed that the air temperatures were generally considerably in excess of the "standard curve" for the period between 3 minutes and 27 minutes after the start of the fire as shown in figure 2. It was reported that the fire in the Cabin Burnout Test was definitely more severe than in the Stateroom Fire Test.

1.4 Structural Fire Protection Regulations

The efforts described above and those of the Safety of Life at Sea Conferences, Inter-Governmental Maritime Consultative Organization committees and the United States Coast Guard have led to the present structural fire protection regulations for ships. The heart of these regulations has remained substantially unchanged for the past few decades. The regulations require the ship to be divided into compartments by bulkheads and decks which have specified degrees of fire endurance (see Title 46 Code of Federal Regulations SubParts 32.57, 72.05, 92.07). The degree required for each bulkhead or deck is determined by its location and the uses of surrounding compartments. The fire endurance of the bulkheads and decks is divided into three classes, A, B, and C. Bulkheads or decks of the "A" class shall be of steel and so constructed that if subjected to the standard fire test, they would be capable of preventing the passage of smoke and flame for one hour. In addition, they shall be insulated so that the average temperatures on the unexposed side would not rise more than 250°F above the original temperature nor would the tempera- ture at any one point rise more than 325°F above the original temperature within the time listed below:

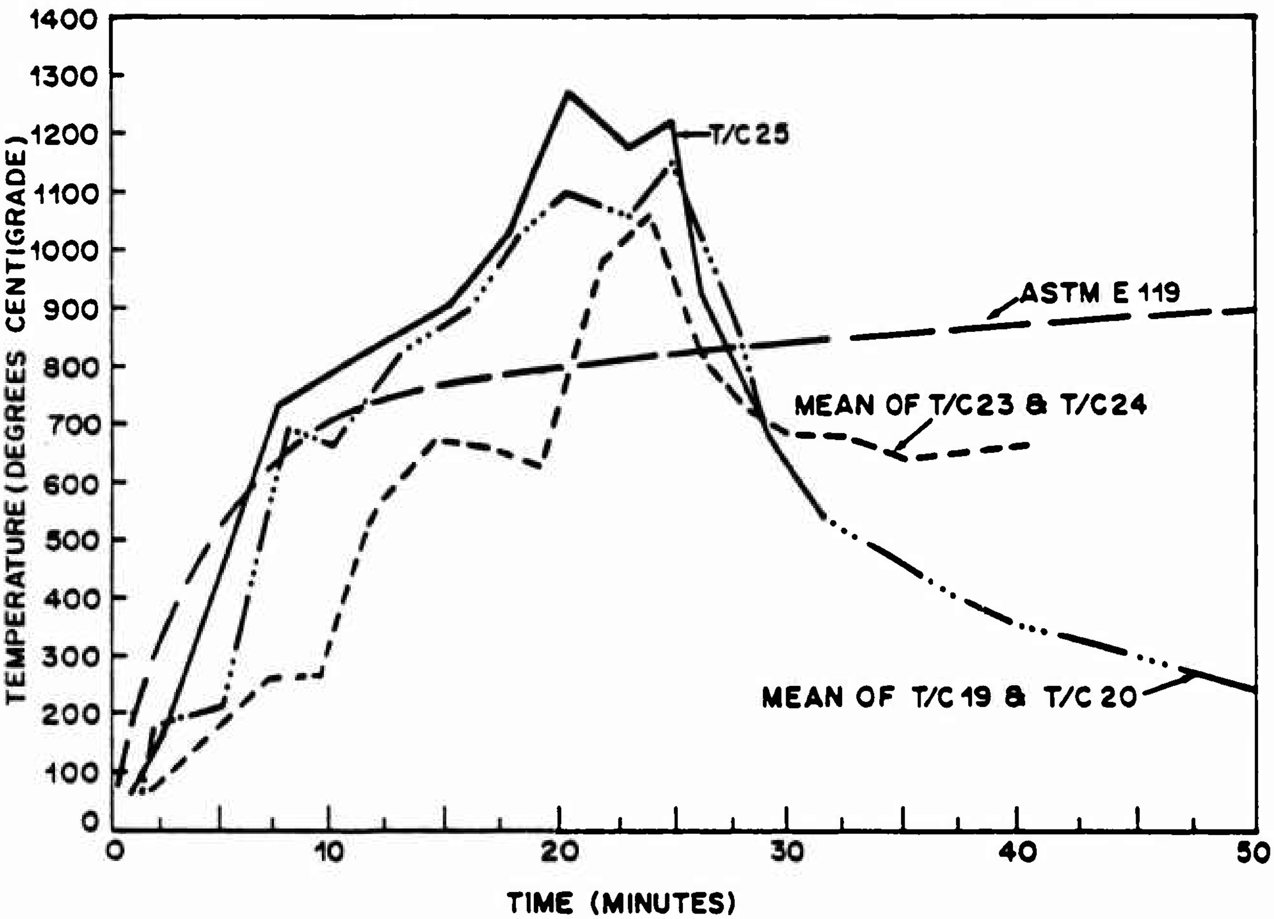


FIGURE 2. Cabin Burnout Test; Temperature Histories

Class A-60	60 minutes
Class A-30	30 minutes
Class A-15	15 minutes
Class A-0	0 minutes (i.e., no insulation requirements)

Bulkheads of the "B" class shall be so constructed that if subjected to the standard fire test, they would be capable of preventing the passage of flame but not smoke for one-half hour. In addition, their insulation value shall be such that the average temperature of the unexposed side would not rise more than 250^{o}F above the original temperature, nor would the temperature at any one point rise more than 405^{o}F above the original temperature within the time listed below:

Class B-15	15 minutes
Class B-0	0 minutes (i.e., no insulation required)

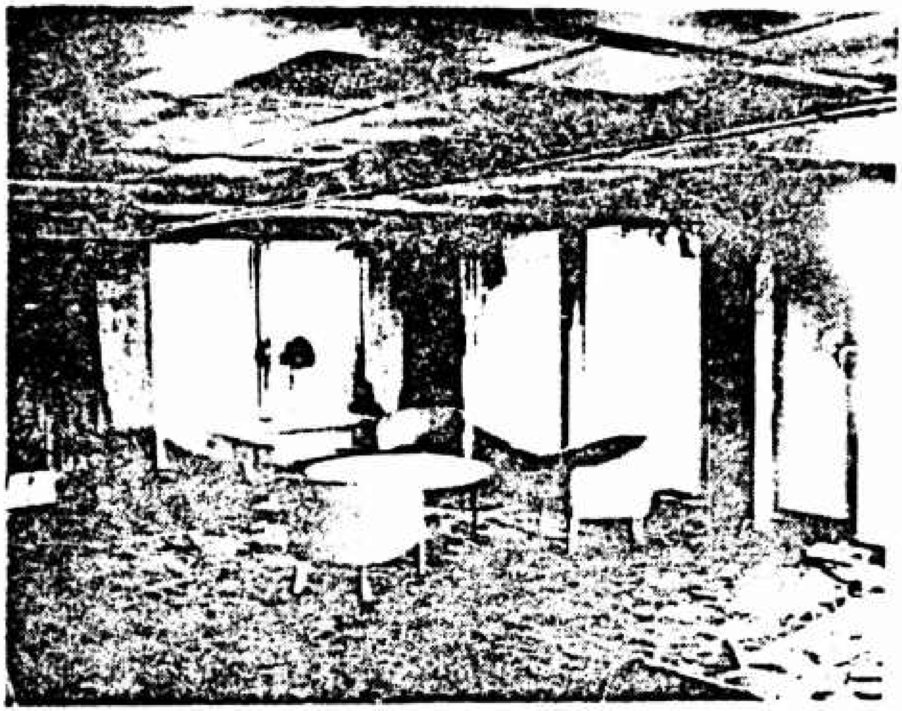
Bulkheads of the "C" class shall be constructed of approved non-combustible materials but do not need to meet requirements relative to the passage of flame or smoke nor the limiting of temperature rise. The standard fire test referred to above is defined in Title 46 Code of Federal Regulations SubPart 164.008. It employs the standard time-temperature curve referred to through- out this introduction.

1.5 SS AUSTRAL ENDURANCE Lounge Fire

Since the implementation of these regulations, the materials used in the outfitting, decorating, and furnishing of compartments have changed. The predominantly cellulosic materials have been replaced to a large degree by plastics and synthetics. Laboratory tests of these materials indicate a higher rate of heat release and smoke production than for cellulosic materials. The 14 July 1973 passenger lounge fire on the SS AUSTRAL ENDURANCE also demonstrated this fact (figure 3).

The freighter was on her maiden voyage from Brisbane, Australia to Auckland, New Zealand when fire broke out in the passengers lounge. The fire, believed to have been ignited by a dropped cigarette, spread from the sofa, which had polyfoam cushions, to the carpet and carpet padding. It produced significant damage in the lounge. Only because of the efforts of two fire parties, which had been previously drilled and which were led by the Chief Officer and Chief Engineer, was the fire brought under control and contained in the lounge. Post-fire observations reported principally by the Chief Officer and Chief Engineer were:

- The sofa was completely consumed
- The wool carpet and the padding were charred in the sofa area
- The ceiling panels (asbestos) were destroyed over the sofa area
- The curtains (70% Mod acrylic - 30% Rayon) were consumed and contributed to the fire spread
- The bulkhead panels (Marinite) remained intact but the wall covering (Vinyl) blistered and charred; however, this did not appear to contribute significantly to the fire
- Open doors from the lounge permitted smoke and heat to enter the passageways



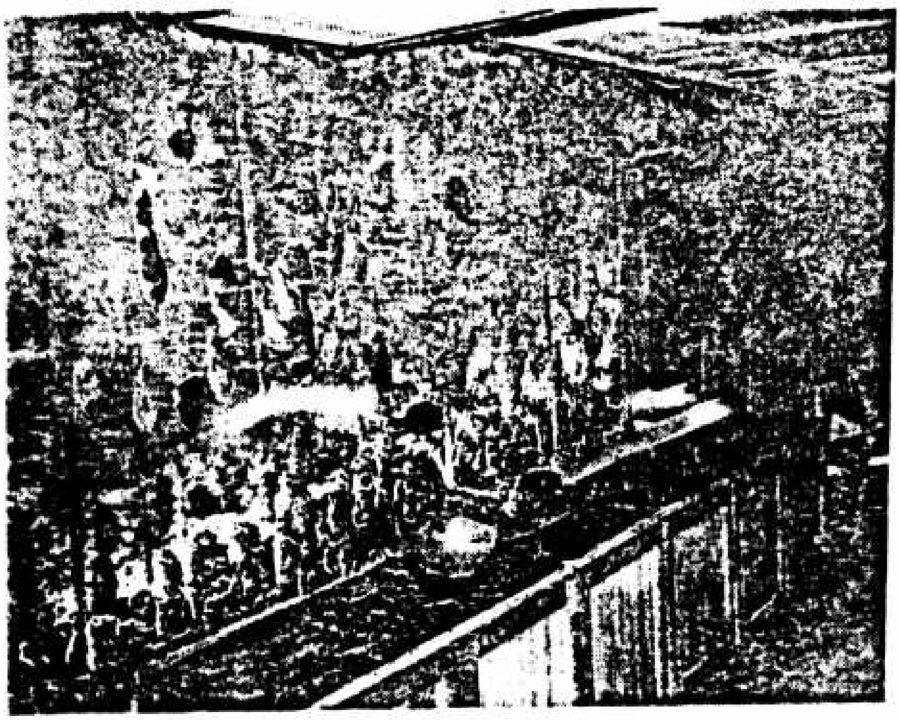


FIGURE 3. Pictures of SS AUSTRAL ENDURANCE Fire Damage

- Smoke was carried by the ventilation system to the 12 passenger compartments forward of the lounge
- Temperatures reached an estimated 1600°F in some areas

It was primarily because of this fire, the efforts of Farrell Lines and the Coast Guards Merchant Marine Technical Division that a re-evaluation of the standard fire test for marine application was undertaken through this research.

2.0 OBJECTIVES

The research project described herein addresses the question, "Does the use of modern materials in the furnishing and decorating of compartments and in the personal effects of crew and passengers sufficiently alter the fuel loading and/or heat release to require the U.S. Coast Guard to re-evaluate its structural fire protection regulations?" The fire performance expected of a shipboard bulkhead is that it will contain the fire and prevent its spread for a reasonable length of time. The same performance is expected of the deck and the overhead. Fire may spread from its enclosure of origin, despite the containment effect of the bulkhead, when its unexposed side becomes hot enough to ignite nearby combustibles, such as drapes or other furnishings. Fire may also spread by transporting thermal energy along with air flowing out of the enclosure. The ventilation provided by either a forced air system or by natural convection through doors and windows, therefore, may have an important effect on the flame spread. Furthermore, the rate of combustion may become ventilation-controlled, when the air supply passage restricts the maximum rate at which oxygen may reach the fire. To address these variables, the project was focused on the following goals with respect to the burnout of a modernly outfitted ship's lounge:

a. Determine the temperature histories during the burnout at different locations in the lounge and compare it with the standard curve presently used by the U.S. Coast Guard.

b. Determine the effects of ventilation on the severity of the fire.

c. Document the general characteristics of the burnout including flame spread, smoke production, and gas production.

d. Document the behavior of the bulkheads during the burnouts with respect to their structural and fire containment properties.

3.0 DESCRIPTION OF THE EXPERIMENTAL SETUP

From the conception of this project, full-scale burnouts of rehabilitated lounges located on the T/V A.E. WATTS at the U.S. Coast Guard Fire and Safety Test Detachment (F&STD) in Mobile, Alabama were anticipated. The WATTS was obtained from the James River, Virginia, reserve fleet just as the NANTASKET was. It was felt that full-scale burnouts would be required to verify any small-scale experiments or information ex- tracted from the literature. The literature search previously discussed and a series of 1/4-scale experiments were undertaken so that the full-scale burn- outs could be effectively designed.

The approach to the burnouts was to duplicate as nearly as possible a ship's lounge and produce a worst-case fire in it. The lounge was outfitted with furnishings which furthered the worst-case philosophy. The total number of burnouts was limited by the funding available. The six that were conducted provided for a duplicate of each of three ventilation configurations but did not permit a statistical treatment of the effects of even the major variables. The exterior environment which affects a fire's progress could not be completely controlled so, its principal physical characteristics were monitored and recorded for comparison.

3.1 Lounge Configuration

The crew's lounge on the boat deck of a roll-on/roll-off cargo ship (Maritime Administration Design C7-S-95A) was modeled. A lounge-type compartment was chosen because of its relatively high fire load and frequent use. It was 23 ft 4 in. by 17 ft 6 in. with a 6 ft 7 in. ceiling height and a deck-to-deck spacing of 8 ft 0 in. The sitting room area (inner room) was 12 ft 4 in. by 17 ft 6 in. and was connected by a 6 ft 6 in. wide floor-to-ceiling opening to a game table area (outer room) which was 11 ft by 17 ft 6 in. as shown in figure 4. A lounge of this configuration was constructed on the port side of the Bridge Deck in the forward deck house of the T/V A.E. WATTS. A mirror image of this lounge was constructed on the starboard side of the bridge deck (see figure 5) and these two lounges were rehabilitated twice each to accommodate the six lounge burnouts.

3.2 1/4-Scale Experiments

The purpose of these experiments was to define a worst-case arrangement of furniture, door positions and ventilation in respect to fire severity in the burnout of the lounge configuration described above. The results were then used to predict the worst-case arrangement for the full-scale lounge burnouts. Other objectives included testing the feasibility of using stain-tubes to measure quantities of toxic fire gases and using motion picture cameras to observe fire growth.

Accurate predictions of a full-scale fire by quarter-scale modeling is difficult because all conditions cannot be scaled. For example, flame height at any given time during a fire is dependent upon fuel geometry, ventilation and the inherent burning characteristics (or combustibility) of the material involved. Since the burning characteristics cannot be scaled, scaling only the fuel geometry and ventilation would result in unrealistic fire spread throughout the compartment. For this reason, the information

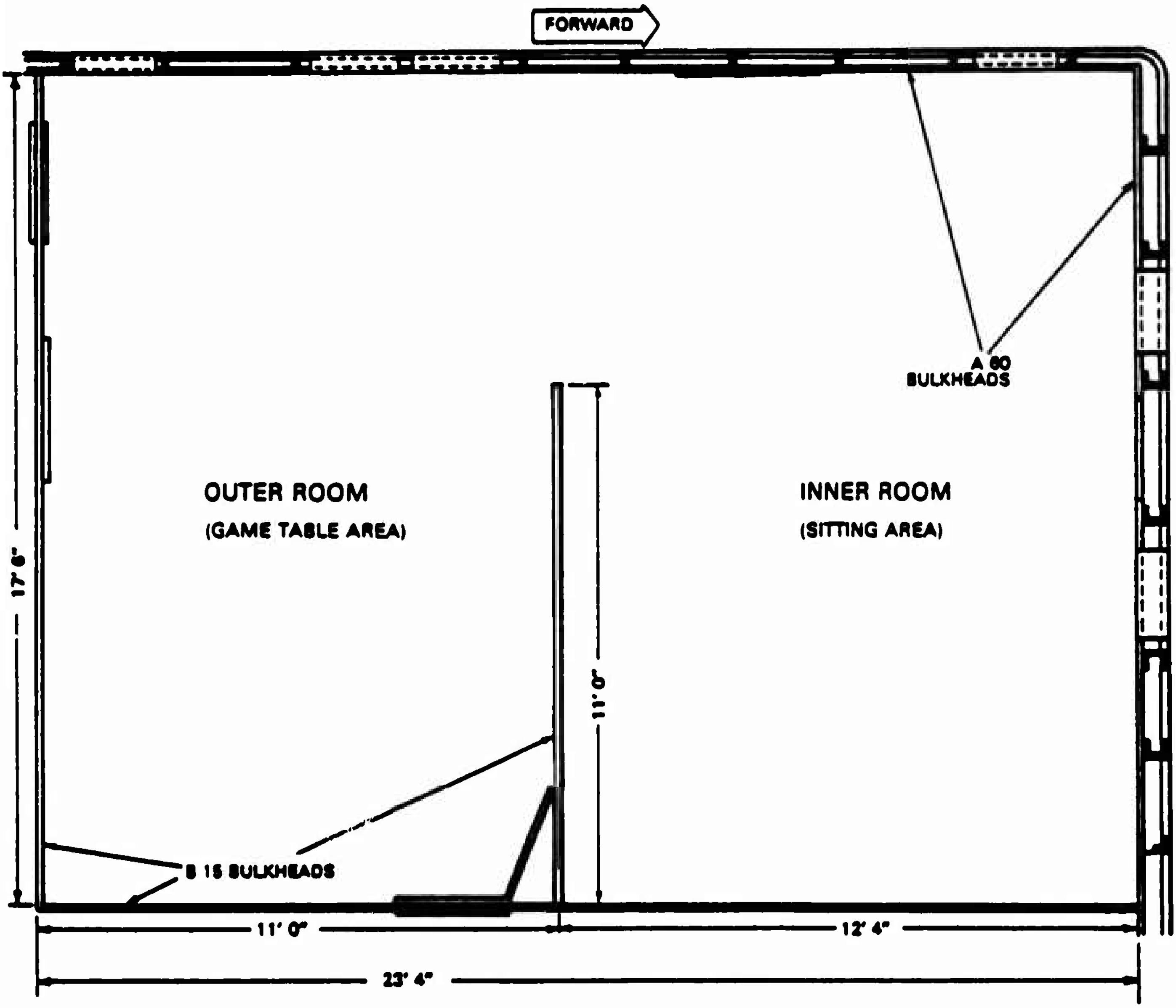


FIGURE 4. Plan View of Lounge

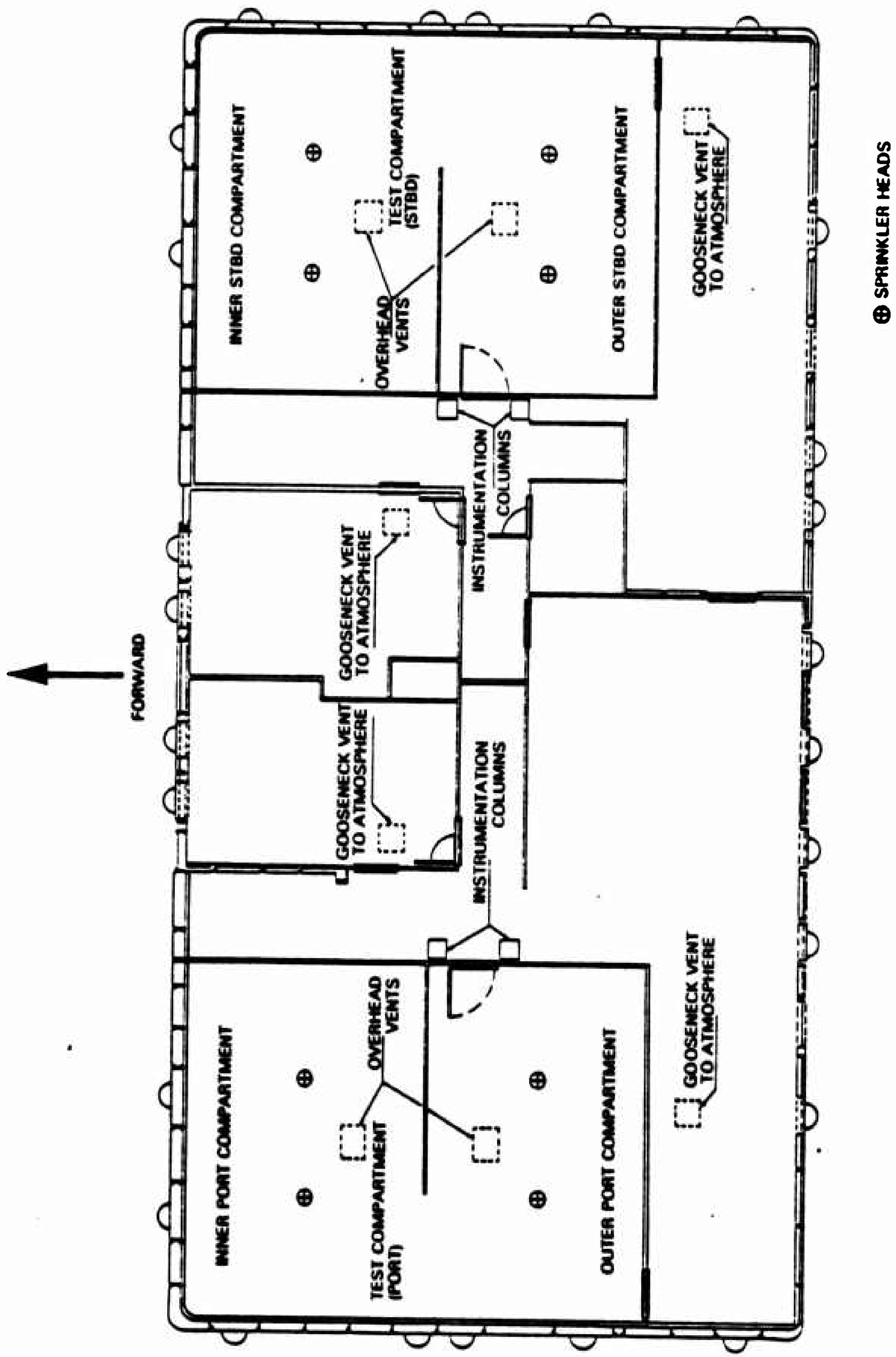


FIGURE 5. Plan View of Bridge Deck Test Area as Configured During Experiments

provided by these experiments was not considered a prediction of the results of full-scale burnouts but provided insight for the design of worst-case arrangements.

The approach taken to scaling in this experimental series is based on testing done by the National Bureau of Standards[6]. In order to provide realistic burning characteristics, fuel (material) thicknesses were not changed. The fuel loading (weight of combustibles per square foot of floor area) and ventilation were reduced by the ratio of floor area in the scaled lounge to the floor area in the full-scale lounge (i.e. 1/16). Since the doorway is a critical factor in compartment ventilation, it is necessary to size the doorway such that it permits 1/16 the air flow of the actual lounge. The wall above the doorway, however, traps the hot combustion products from the fire and is critical to the phenomena taking place in the room. Thus it is desirable to scale the doorway height by the scale factor (i.e. 1/4). This means that the width of the doorway must be used to maintain the air flow proportionality in the model. Air flow varies directly as width times height $^{3/2}$.

$$Wm\ Hm^{3/2} = 1/16\ Wa\ Ha^{3/2}$$

where m denotes the model
a denotes the actual lounge

therefore $\frac{Wm}{Wa} = \frac{1}{16}\left(\frac{Ha}{Hm}\right)^{3/2}$

substituting $Hm/Ha = 1/4$

thus $\frac{Wm}{Wa} = \frac{1}{2}$

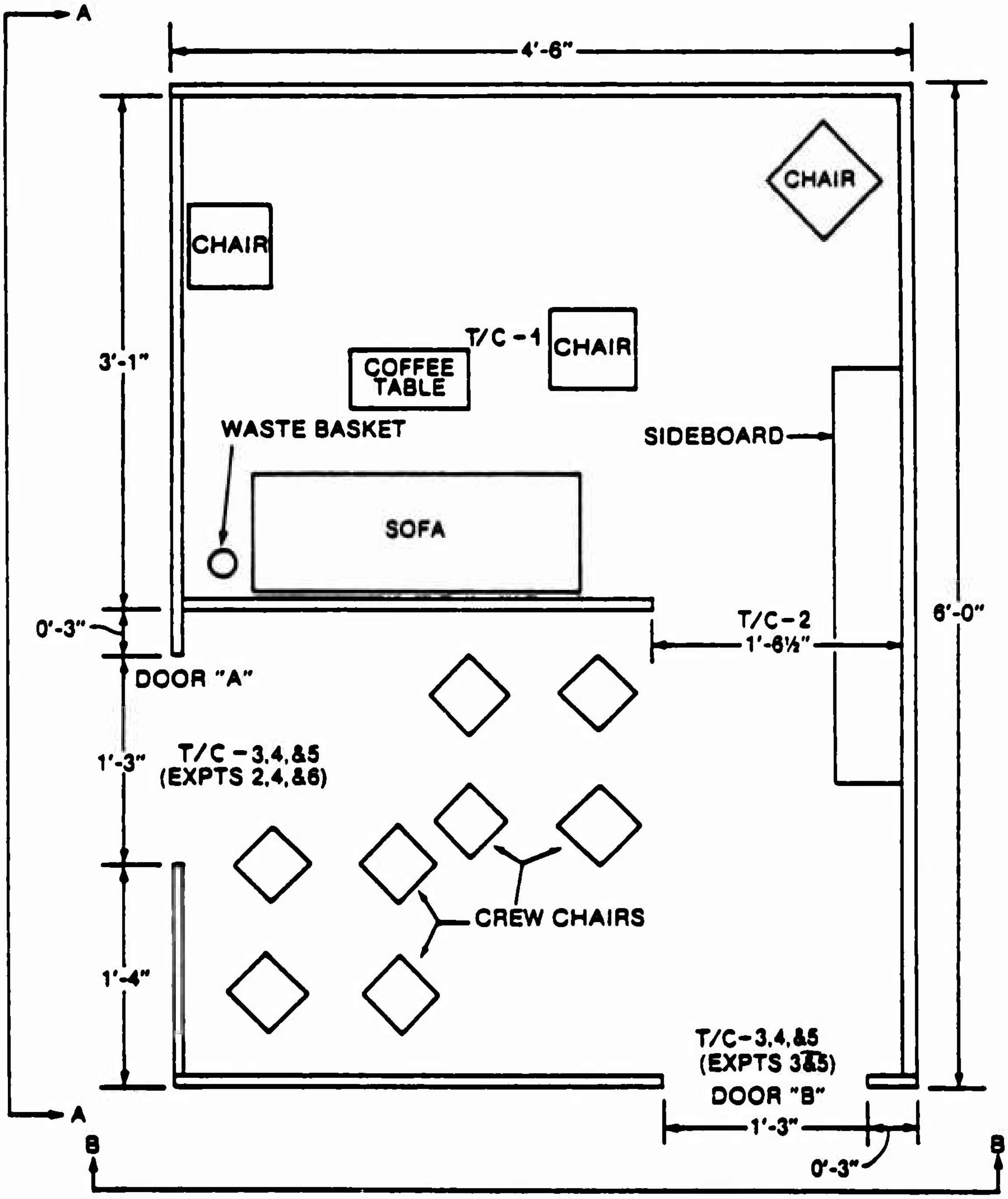
Therefore to maintain the air flow ratio of 1/16 the door width must be scaled by 1/2.

The lounge's floor plan and arrangement were designed to simulate 1/4-scale models of the full-scale lounges (see figures 6A and 6B). Six lounges were constructed as follows:

Ceiling: 3/4" Marinite 36 paneling lined with 1" Microlite fiberglass insulation and Johns-Manville acoustical ceiling tile.

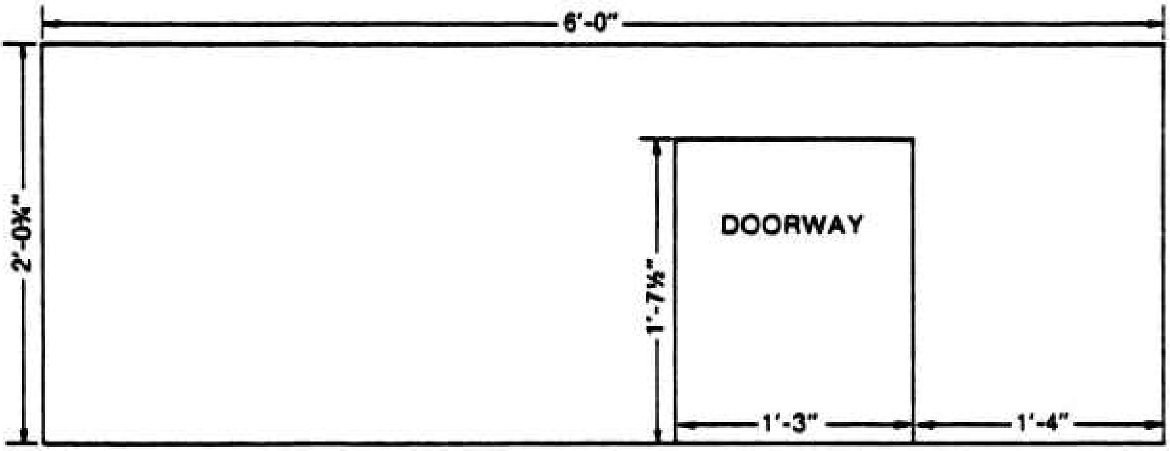
Walls: 3/4" Marinite 36 paneling lined with Westinghouse general purpose Micarta plastic laminate held in place with screws.

Deck: 24 gauge steel covered with 1/2" solid polyurethane foam padding and 40 ounces per square yard, sheared, plush, acrylic carpet.

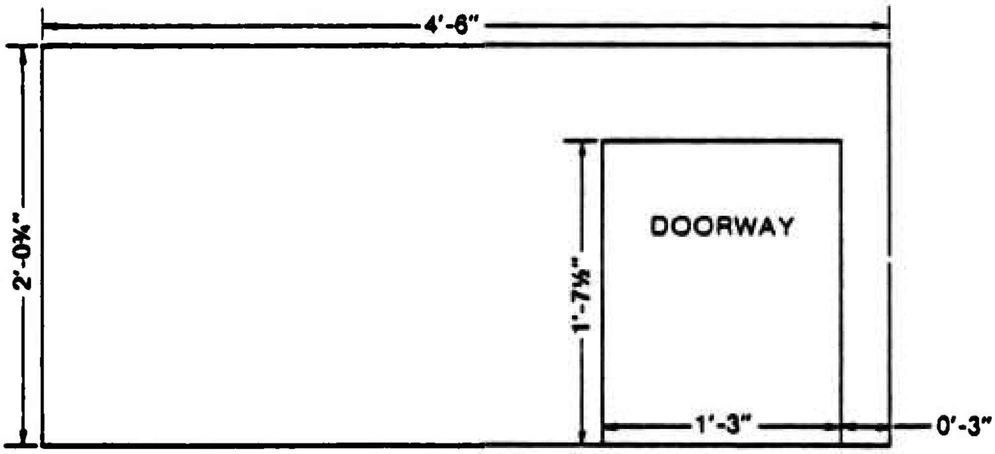


T/C = THERMOCOUPLE NUMBER	HEIGHT ABOVE DECK
1	1'0"
2	1'11"
3	1'6"
4	1'1"
5	0'7"

FIGURE 6A. Plan View of 1/4 Scale Lounge



ELEVATION A-A



ELEVATION B-B

FIGURE 6B. Elevations of 1/4 Scale Lounge

Analysis of fire gases using stain tubes was attempted at 3-minute intervals in experiments 2, 3, 4, 5 and 6. Small holes were drilled in a 4" duct leading from the top of lounge doorway so that the stain tubes could be inserted into the stream of hot fire gases. Carbon monoxide and hydrogen chloride tubes manufactured by Mine Safety Appliances were used with an MSA syringe-type pump. Hydrogen cyanide and carbon dioxide tubes manufactured by Draeger were used with a Draeger Bellows Pump. None of the gas analysis tests provided satisfactory results because the stain tubes were improperly sized.

Ventilation was provided through the two door openings in experi- ments 2, 3 and 6. In experiments 1, 4 and 5, forced ventilation was provided at the center of the ceilng of the inner room through a six-inch duct con- nected to a small fan. The outlet of the duct into the compartment had a diffuser installed to insure air circulation throughtout the compartment. The flow rate was scaled so that the model compartment had the same amount of airflow per square foot of floor area as the full-scale compartment.

Area of full-scale lounge:	18' x 24' = 432 ft^2
Area of model lounge:	4.5' x 6' = 27 ft^2
Flow rate in full-scale lounge:	450 cfm
Flow rate in model lounge:	450 (27/432) = 28.1 cfm

Each lounge was furnished with the following items (see figure 7):

Items	Scaled Weight
8 crew chairs	17.8 grams of polyurethane foam per chair
1 couch	1162.3 grams of wood
	1175.86 grams of cushion material
3 lounge chairs	312.0 grams of wood per chair
	374.9 grams of cushion material per chair
1 coffee table	567.5 grams of wood
1 sideboard	567.5 grams of wood

The weight of each item of furniture was calculated so that the model lounges would have the same fire load as the full-scale lounges. On items that contained two or three different combustible materials, such as the couch and the lounge chairs, each material was scaled separately. The weight of the coffee table and sideboard were estimated since none were available for weighing. Six 1/8 in. diameter type K (nickel-chromium vs. nickel-aluminum) thermocouples were located as shown in figure 6A for experiments 2-6.

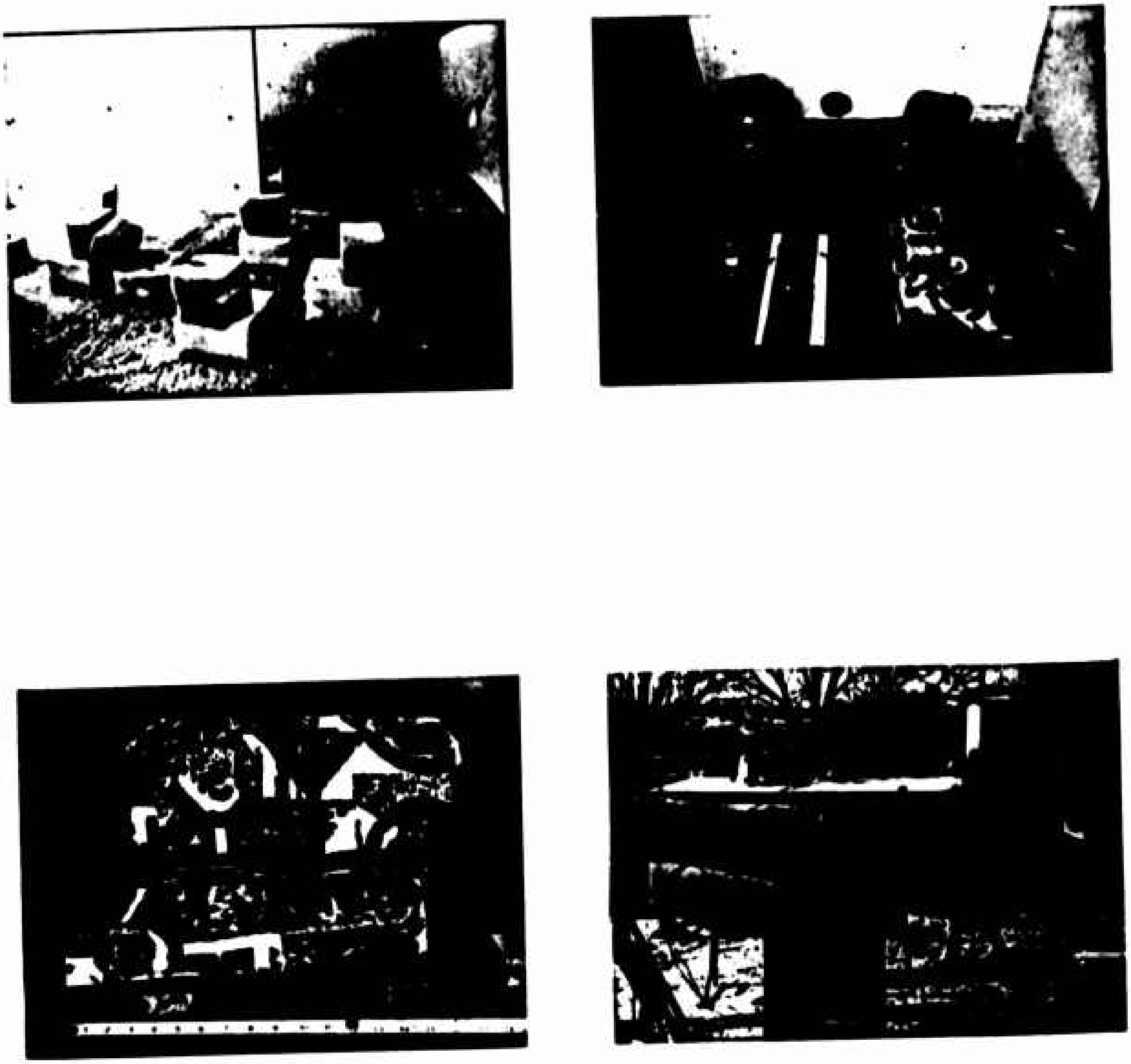


FIGURE 7. Pictures of 1/4-Scale Setup

3.2.1 Results Of Experiment 1

Experiment 1 was a preliminary test to determine the approximate burn time and the size of the ignition source for subsequent tests. No temperature readings were taken during the test. Forced ventilation was applied at a rate of 28 cfm. Only door A was open during the test. The ignition source consisted of three pieces of 8-1/2 in. x 11 in. notebook paper in a small can, simulating a waste basket placed next to the couch as shown in figure 6.

The fire spread rapidly throughout the lounge and total involvement was noted in the inner room at 12 minutes and 30 seconds into the test. Less than one minute later, at 13 minutes and 20 seconds, the outer room was totally involved. The fire began to recede at 14 minutes, 50 seconds. The remains of the laminated plastic wall covering collapsed onto several pieces of furniture so it was held in place by 3/8 in. screws in the remaining experiments.

3.2.2 Results Of Experiments 2 And 3

Experiments 2 and 3 were designed to observe the fire growth in the lounge with no forced ventilation. The fire was ventilated through door openings A and B in experiment 2 and only through door opening A in experiment 3. The ignition source consisted of a few ounces of paper placed in the waste basket at the edge of the sofa. In both experiments, difficulty in achieving ignition of the sofa was experienced. Only a small area of the sofa was ignited by the ignition source. This resulted in a slower spreading fire than in later tests. Total lounge involvement did not occur in experiments 2 and 3 until approximately 12 minutes and 15 minutes, respectively. The fire did seem to grow to approximately the same intensity after sufficient time was allowed for the flames to develop.

3.2.3 Results Of Experiments 4 And 5

Forced ventilation was used in experiments 4 and 5 at a rate of 28 cubic feet per minute. Experiment 4 was conducted with both door A and door B open while only door A was opened in experiment 5. A waxed paper cup was used in experiment 4 in place of the metal container to hold the ignition source. Several small candles were also added to the paper to increase the size and the burn time at the ignition source. In experiment 5, candles and paper were again used as the ignition source, but they were placed in a metal waste basket container.

The increase in size of the ignition sources resulted in much faster spreading fires. Total involvement occurred in less than 8 minutes in experiment 4 and just over 8 minutes in experiment 5. The intensity of the fire did not appear to be substantially increased, but the rate at which the fire developed was much greater.

3.2.4 Results Of Experiment 6

In order to determine if the rapid development of the fires in experiments 4 and 5 were a result of forced ventilation or the increase in size of the ignition source, experiment 6 was conducted under conditions

similar to experiment 2, using a metal "waste basket" container so that the ignition source would have a longer burning time. Total involvement of the inner room occurred in approximately 8 minutes. The outer room was totally involved in approximately 10 minutes. The maximum temperatures measured were generally less than those measured in experiment 4, but greater than those measured in experiment 5.

3.2.5 Conclusions Of 1/4-Scale Experiments

Test results indicated that the model lounges had adequate ventilation without the use of forced ventilation. One door opening provided sufficient ventilation to result in total burnout of the lounge (see figure 8). The rate of fire spread appeared to be more dependent on the size and placement of the ignition source than on ventilation restrictions. In those tests where larger ignition sources were used, the fire developed more rapidly, resulting in a steeper slope for the time-temperature curve. The time-temperature curves (see figure 9) indicate that no single test resulted in a "most severe" time-temperature relationship at all thermocouple locations. Because the size of the ignition source was such a factor in the rate of fire development, for comparative purposes the graphical analysis was initiated at the time individual thermocouples reached 300^{o} F. The small-scale tests were not conclusive in establishing a "worst case" based upon a time-temperature relationship.

3.3 Full-Scale Lounge Construction

The interior of the Bridge Deck was gutted in the area of the lounges so that only the steel plate, beams, stringers and port lights forming the deck, weather bulkheads, and overhead remained intact. The lounges were then constructed as shown in figure 4 in accordance with Title 46 Code of Federal Regulations, parts 32.57 or 92.07. The perimeter bulkheads and the overhead were "A" class divisions. All materials used in their construction were types that are approved under the applicable subpart of Title 46 Code of Federal Regulations as follows:

Material Application	Subpart
Deck Coverings	164.006
Structural Insulations	164.007
Bulkhead Panels	164.008
Incombustible Materials (Ceilings)	164.009
Interior Finishes	164.012

The specific materials, general information, and ambient conditions for each lounge burnout are listed in table 1.

The bulkhead panels were supported at the bottom by a channel welded to the deck. Adjacent panels were supported by typical steel marine joiner system H-posts. The H-posts consisted of matching male and female sections, one on each side of the bulkhead panels, which are assembled by pushing them together to engage a spring clip arrangement. Once assembled, the two adjoining bulkhead panels are clamped between opposite H-post flanges and held securely in place by the friction force developed between the engaged male/female spring clip sections. For bulkhead disassembly, the two H-post sections may be pried apart to release the bulkhead panels. Completely new

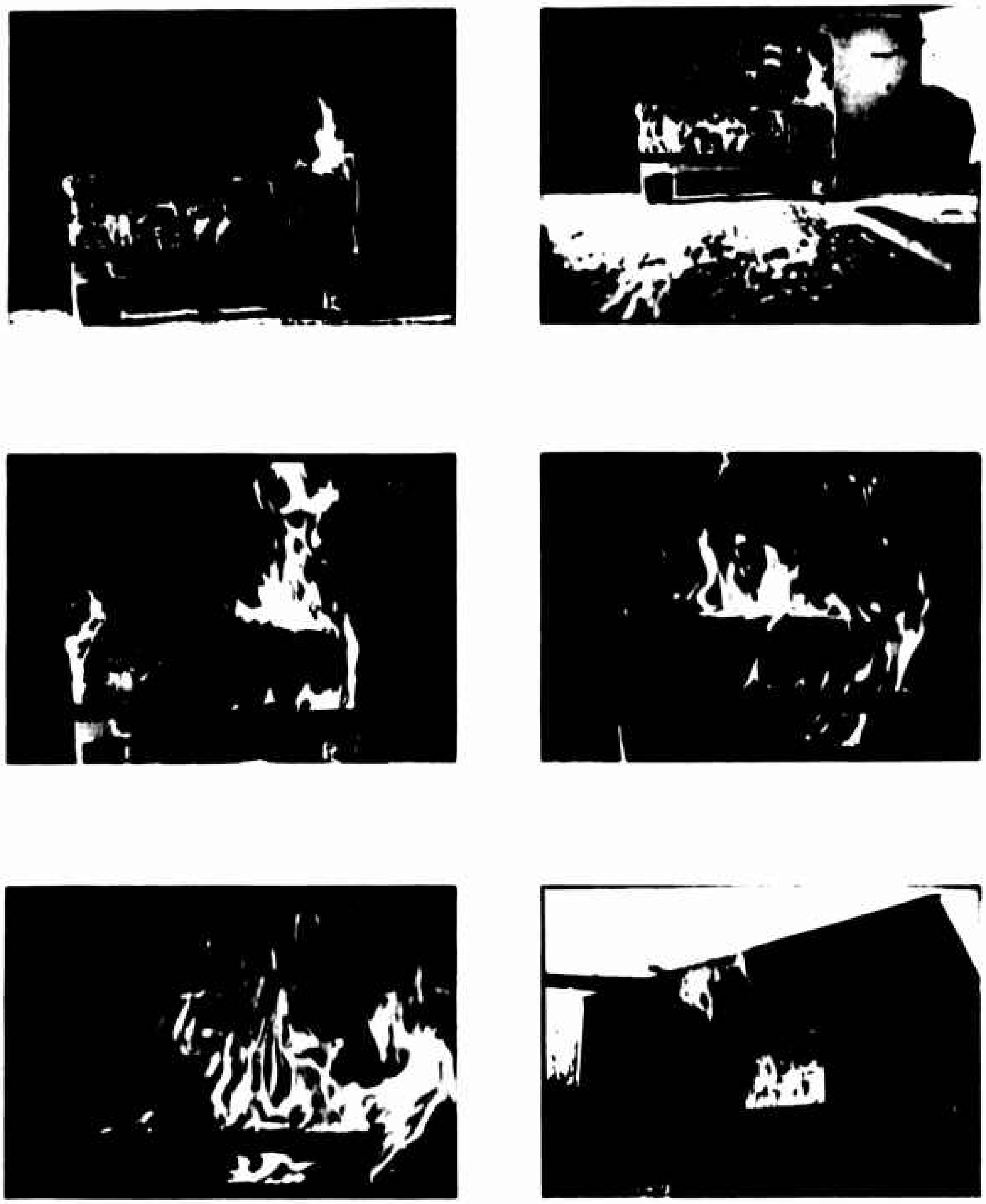


FIGURE 8. Picture Sequence Of A 1/4-Scale Lounge Experiment

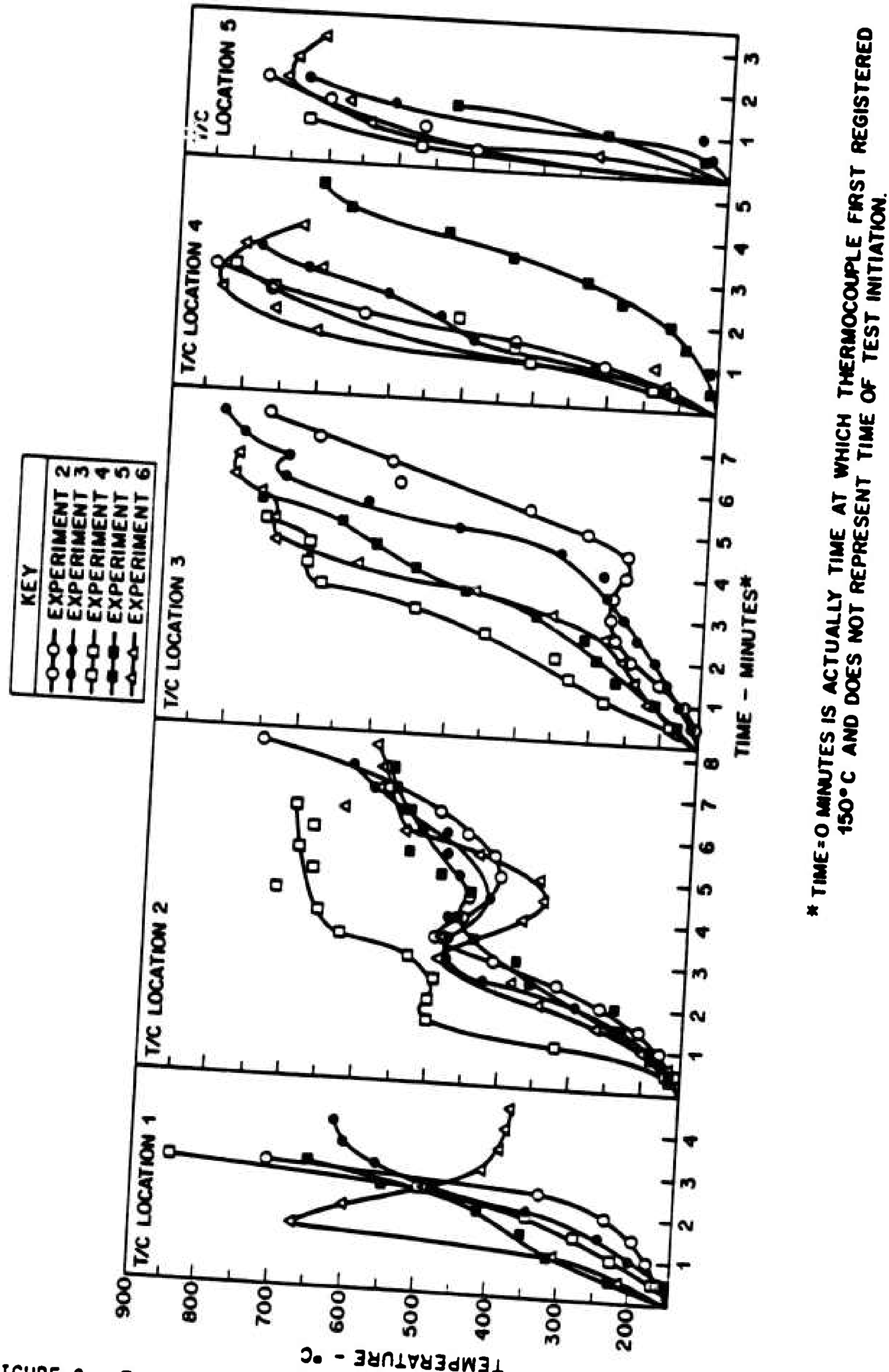


FIGURE 9. Temperature Histories of the 1/4 Scale Lounge Experiments

TABLE 1

GENERAL INFORMATION, CONSTRUCTION MATERIALS, AND AMBIENT CONDITIONS FOR BURNOUT

LOUNGE BURNOUT NUMBER	1	2	3	4	5	6
General Information						
Date of Burnout	22 Apr 77	27 Apr 77	10 Oct 77	17 Oct 77	31 Jan 78	03 Feb 78
Beginning of Burnout (24-hour clock)	1658	1218	1250	1200	1324	1100
Length of Burnout (minutes)	57	70	62	62	60	60
Location on Bridge Deck	Port Side	Stbd Side	Port Side	Stbd Side	Port Side	Stbd Side
Ventilation Configuration	Closed	Closed	Passive	Forced	Forced	Passive
Construction Materials						
Deck Covering	Plush sheared pile acrylic (100% Acrilon) carpet "Magee Resource" weighing 42.4 ounces/square yard on 1/2-inch polyurethane foam pad. For carpet ASTM E84-68, Flame Spread = 46, Smoke Density = 140, Fuel Contributed = 0					
Insulation	Fiberglass structural insulation (6 pounds/cubic foot density) used as follows: 2-inch thickness in exterior (A-60) bulkheads, 4 inches on underneath side of overhead, and 2-inch thick wrap on beams and stringers.					
Bulkhead Panels	M-36	M-36	M-36	M-XL	M-36	M-XL
Bulkhead Veneer	PFR	PFR	PFR	FR	PFR	FR
Ceiling Panels	C-1	C-1	C-2	C-2	C-2	C-2
Ambient Conditions						
Outside: Temperature	76°F	85°F	80°F	80°F	39°F	45°F
Relative Humidity	Rain		41%	40%	70%	59%
Wind Speed	2-4 mph	0-3 mph	0	2-4 mph	3-5 mph	0-3 mph
Wind Direction	NE	NE	N/A	N/A	NE	N
Barometric Pressure (in Hg)			29.99	30.2		30.3
In Lounge: Temperature	74°F	72°F	70°F	71°F	53°F	55°F
Relative Humidity	81%(rain)	56%	56%	55%	53%	49%

KEY:

M-36 = Marinite 36 marine joiner panel made by Johns-Manville, 7/8-inch thick including two 1/16-inch plastic veneers.

M-XL = Marinite XL asbestos-free marine joiner panel made by Johns-Manville, thickness same as above.

FR = Micarta plastic laminate type FR manufactured by Westinghouse Electric Corporation. See below for fire hazard classification.

PFR = Micarta plastic laminate type PFR manufactured by Westinghouse Electric Corporation. See below for fire hazard classification.

FIRE HAZARD CLASSIFICATION (ASTM E-84)
(Based on 100 for Untreated Red Oak)

Laminate Type	FR	PFR
Flame Spread	15	15
Fuel Contributed	20	5
Smoke Developed	5	10

C-1 = Perforated marine veneer, 3/16 inches thick, painted white, and manufactured by Johns-Manville.

C-2 = Perforated aluminum sheets, 0.091 inches thick, painted white, and manufactured by Beckley Perforating Company.

joiner systems were used in each lounge constructed. The bulkhead panels and H-posts extended above the ceiling to within 2 inches of the insulation above. The ceiling consisted of drop-in panels supported at the bulkhead by continuous steel angles and in the interior by a grid work of steel tee's.

3.4 Furnishings and Other Combustibles

The lounges were outfitted with furniture which generally conformed to the U.S. Maritime Administration's specifications for "Officer and Crew Standard Furniture" published in June 1960. A high fire risk was provided by the use of hazardous materials and by positioning the furniture and other combustibles in reasonably hazardous locations (see figure 10). Typical distribution of the furniture and combustibles is shown in figure 11. A listing of the type and quantity of all combustibles is presented in table 2. This resulted in a fuel load of 2.5 pounds per square foot of floor area of the lounge. The fuel load is defined as the quantity of fuel available in a fire area while the fire load is the amount of fuel actually consumed in the fire. In terms of total potential heat, the fuel load was 21,200 BTU per square foot. A closer look shows that the inner room where the ignition source was located had a fuel load of 3.1 pounds per square foot or 25,500 BTU per square foot. Thus, the area where the fire developed had a heavier fuel load. These loads are compared below to the fuel loads in previous tests. It can be seen that they are only 1/3 to 1/2 as formidable.

COMPARATIVE FUEL LOADS

	LBS/FT^2	Btu/FT^2
NANTASKET	5.0	41,000
Stateroom	5.1*	41,500
Cabin Burnout	7.5*	61,400
Lounge Burnout		
Average	2.5	21,200
Inner Room	3.1	25,400

*An average heat of combustion of 8,200 Btu per pound was assumed to calculate these figures.

3.5 Ventilation

A major variable affecting the behavior of any fire is ventilation. Ventilation systems in ships lounges typically force air through louvered terminals in the overhead. Exhaust is typically drawn through open or partially louvered doors, into a passageway and then out a duct by a fan. Lounge doors are often propped open when the ship is at sea. A common procedure when a fire is discovered is to shut off the mechanical ventilation system so as not to force feed the fire with air. When this is done, manual fire dampers in the duct work may or may not be closed depending on the knowledge and state of confusion of the crew.

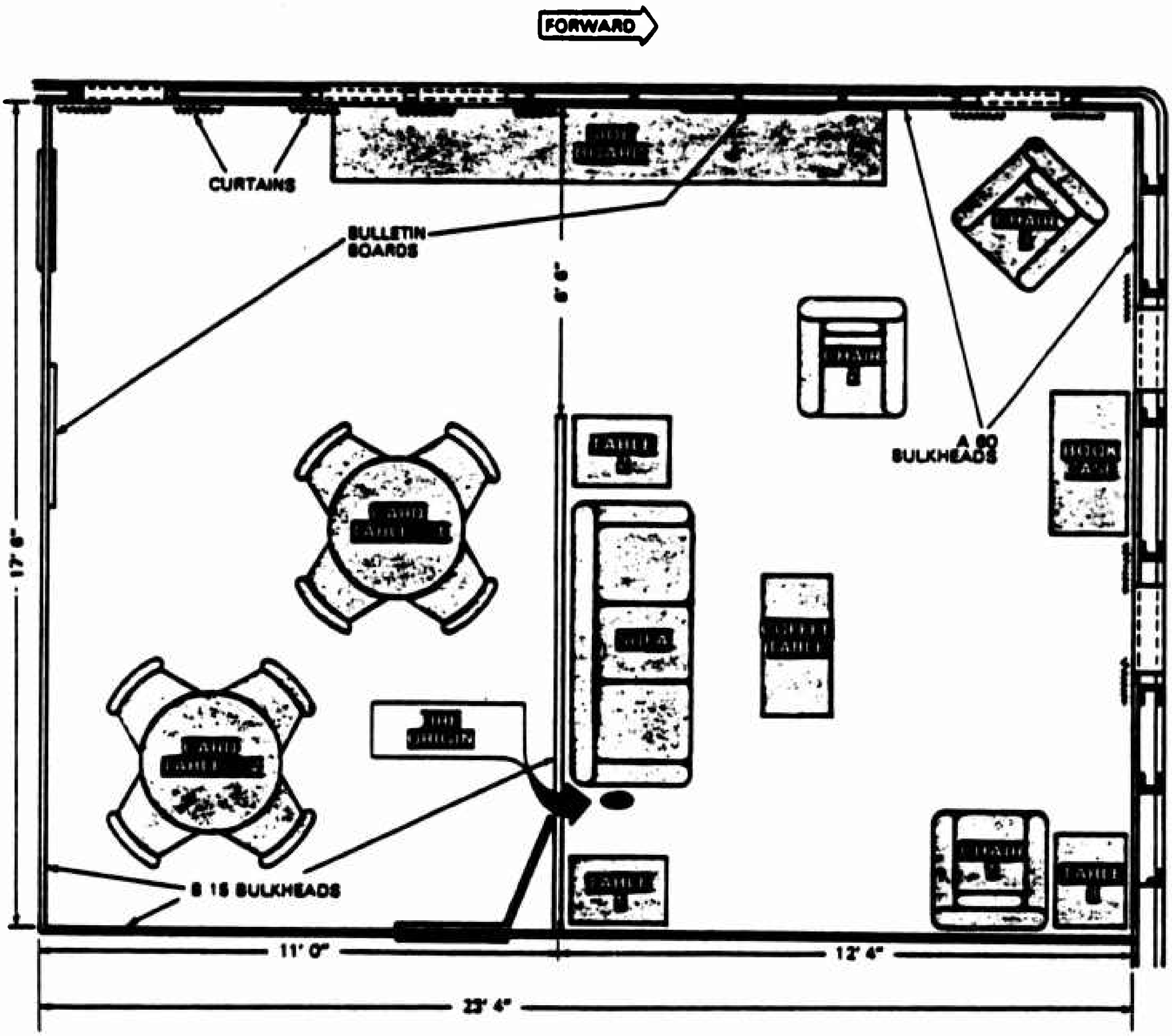


FIGURE 10. Lounge Plan (Port Side) Showing Furniture and Combustible Locations

FIGURE 11. Furniture and Combustibles Distribution

TABLE 2

COMBUSTIBLES IN EACH TEST COMPARTMENT

	Total Quantity In Both Rooms	Inner Room: Total Weight Before Test (lbs)	Inner Room: Heat Content (KBTU)	Outer Room: Total Weight Before Test (lbs)	Outer Room: Heat Content (KBTU)
Furniture:					
Sofa[1]	1	74.1	590		
End table tops[1]	3	30.0	244		
Lamp shades[2]	3	1.5	11		
Coffee table top[1]	1	17.5	142		
Lounge chairs[1]	3	129.0	1036		
Magazine stand top[1]	1	19.0	155		
Sideboard top[1,3]	1	66.0	537	44.0	358
Card table tops[1]	2			24.0	195
Metal chairs (combustible cushions)[1]	8			31.2	340
Bulletin boards[2]	2	10.5	85	10.5	85
Total furniture		347.6	2800	109.7	978
Wall and floor coverings:					
Carpet[1]	409 sft	123.0	1113	109.0	987
Carpet pad[1]	409 sft	10.6	133	9.4	118
Wall covering (Micarta)[1]	644 sft	137.2	1086	116.8	925
Total wall and floor coverings		270.8	2332	235.2	2030
Loose combustibles[2]		47.0	343	22.5	164
Ignition source (naphtha)[2]		2 oz	2		
Subtotal combustibles[4]		665.5	5477	367.4	3172

TOTAL COMBUSTIBLES 1032.9 LBS or 8649 KBTU

Note:

1. Heat content computed from heat value test results of samples taken from each.
2. Heat content estimated.
3. The sideboard was partly in each room.
4. The variation in the total heat content in each room from one test to another was less than 1.9%

The ventilation system used in the lounges was therefore designed to provide three different conditions; forced ventilation, passive ventilation and closed ventilation. Forced ventilation simulates a ship in the normal operating condition. Passive ventilation simulates the condition of the mechanical ventilation fans being shut off after fire detection. Closed ventilation simulates the condition of the manual fire dampers being closed. Thus closed ventilation isolates the lounge from the outside and air can only be drawn from the bridge deck. The forced and passive ventilation conditions permit air to be drawn from outside as well as from the bridge deck. In all cases, the door in the aft bulkhead was closed while its louvered portion (approximately 2.25 sq ft) remained open. The ventilation conditions had the following characteristics:

Forced Ventilation - Air was forced into the lounge through two terminals with aluminum diffusers at 360 cu ft per minute. One terminal was located at the ceiling of the inner room and the other at the ceiling of the outer room as shown in figure 5.

Passive Ventilation - The two terminals described above were ducted together and open to the atmosphere through ducting with a minimum cross sectional area of 2.1 sq ft.

Closed Ventilation - The two terminals described above were closed off with metal dampers 1 foot above the diffuser.

During each burnout test, all port lights, exterior doors and doors dividing the bridge deck approximately on the centerline of the ship were closed as shown in figure 5. This permitted ventilation through the open lounge door (14.2 sq ft) into a volume of approximately 7800 cubic feet. Each half of the bridge was vented to atmosphere through two gooseneck vents with a combined area of 2.5 sq ft and through cracks around doors and holes in the deck with an approximate total area of 1.5 sq ft. An additional volume of fresh air was supplied to the test area via the cooling air flow in the instrumentation columns. This resulted in approximately 2300 cfm of air being supplied high in the area. The lounge not being tested was closed, the door louvers covered, and the space overpressurized by forcing 2300 cfm of air through a port light. This was done as a precaution against its accidental ignition while the lounge being tested was burnt out.

3.6 Ambient Conditions

While it was impossible to control the weather in the vicinity of the bridge deck for the tests, an attempt was made to control the temperature and relative humidity of each compartment. An air conditioning system was employed for 24 hours prior to test initiation. This sytem was used to maintain the relative humidity at 50 $\pm$ 5 percent except in Burnout 1. The actual ambient conditions at the time of each burnout are shown in table 1.

3.7 Ignition Source

The ignition source was a 2-gallon metal waste can containing 5 quart-size plasticized paper milk cartons. It was placed between the sofa and the corner of the room near enough to the sofa to allow direct impingement of

flame upon the back cushion and arm rest. Exact arrangement of the milk cartons in the waste can and the placement of the can were identical in the six burnouts. Ignition of the milk cartons was achieved by placing a small amount (see table 2) of flammable liquid in the bottom of the waste can, but not over the milk cartons, and lighting the liquid with a match. The distance of the sofa from the bulkheads was also held constant.

3.8 Data Collection and Instrumentation

Up to eighty-eight instruments or transducers were used to measure physical properties immediately prior to, during and immediately after each burnout. Each of these was connected electrically to a particular channel. Data was recorded from each channel on a data logger or on strip charts. The data logger permitted the sampling of each channel once every 2 seconds (Burnouts 1 and 2) or 30 seconds (Burnouts 3-6). The strip charts sampled the channels continuously. A summary of the data collection characteristics and numbers of instruments appears in table 3. A description of the various transducers follows. The location of each one is approximated with its channel number in figures 12 and 13 while the exact locations are tabulated in appendix A.

3.8.1 Temperature Measurement

The primary data taken were air temperatures adjacent to the bulkheads, the deck and the overhead. Surface temperatures on the exposed and unexposed sides of the Marinite panels were also measured. Thermocouples were randomly placed to document temperatures in these areas.

The majority of the thermocouples were made up of 20-gauge, type K (nickel-chromium vs nickel-aluminum) wire with glass fiber insulation and an exposed junction formed by a crimp tip. Several thermocouples (4 in Burnouts 1 and 2, and 6 in Burnouts 3-6) were air aspirated[7] as shown in figure 14. The welded thermocouple bead was 0.70 inches in diameter and was recessed 0.5 inches inside a stainless steel tube (0.25 in. outside diameter, 0.005 in. wall thickness). The aspirated air velocity was 8 meters per second.

The millivolt signals produced by all of the thermocouples were processed by an ice point reference circuit internal to the data logger. This circuit matches both the slope and curvature of the type K thermocouple output characteristics and converts the signal to degrees centigrade. The maximum expected error at $0^{o}C$ is $\pm$ $0.5^{o}C$ and at $1400^{o}C$ is $\pm$ $1.0^{o}C$.

3.8.2 Smoke Density

Smoke density was measured horizontally at three levels in the doorway. These levels were 18, 45 and 72 inches above the deck (see figure 13). The measurements were made with optical density meters which measured the attenuation of a collimated visible light beam impinging on a phototube. The light source was an incandescent lamp (GE PR-15) collimated with small diameter aluminum tubes. The receiver used a phototube (RCA IP39) which is sensitive in the human visual spectrum (3000 angstrom short wavelength cutoff, 4000 angstrom peak, and 6500 angstrom long wavelength cutoff). The path length between the light source and the receiver was 30.0 $\pm$ 0.25 inches.

TABLE 3

INSTRUMENTATION SUMMARY

	BURNOUTS 1 AND 2	BURNOUTS 3 THROUGH 6
Data Collection:		
Total instrument channels	65	88
Data logger channels	59	88
Data logger sampling interval	3 channels/second	3 channels/second
Time to scan all channels	20 seconds	30 seconds
Number of scans per hour	180	120
Number of strip chart recorders	6	6
Instruments:		
Thermocouples	40	60
Smoke density meters	3	3
Air velocity probes	6 on-strip charts*	7
Gas concentrations		
Oxygen analyzers	2	3
Carbon monoxide analyzers	2	2
Carbon dioxide analyzers	2	2
Weight loss (load cells)	3	3
Heat flux transducers		
Calorimeters	5	4
Radiometers	2	3

* Did not work during Burnout 2

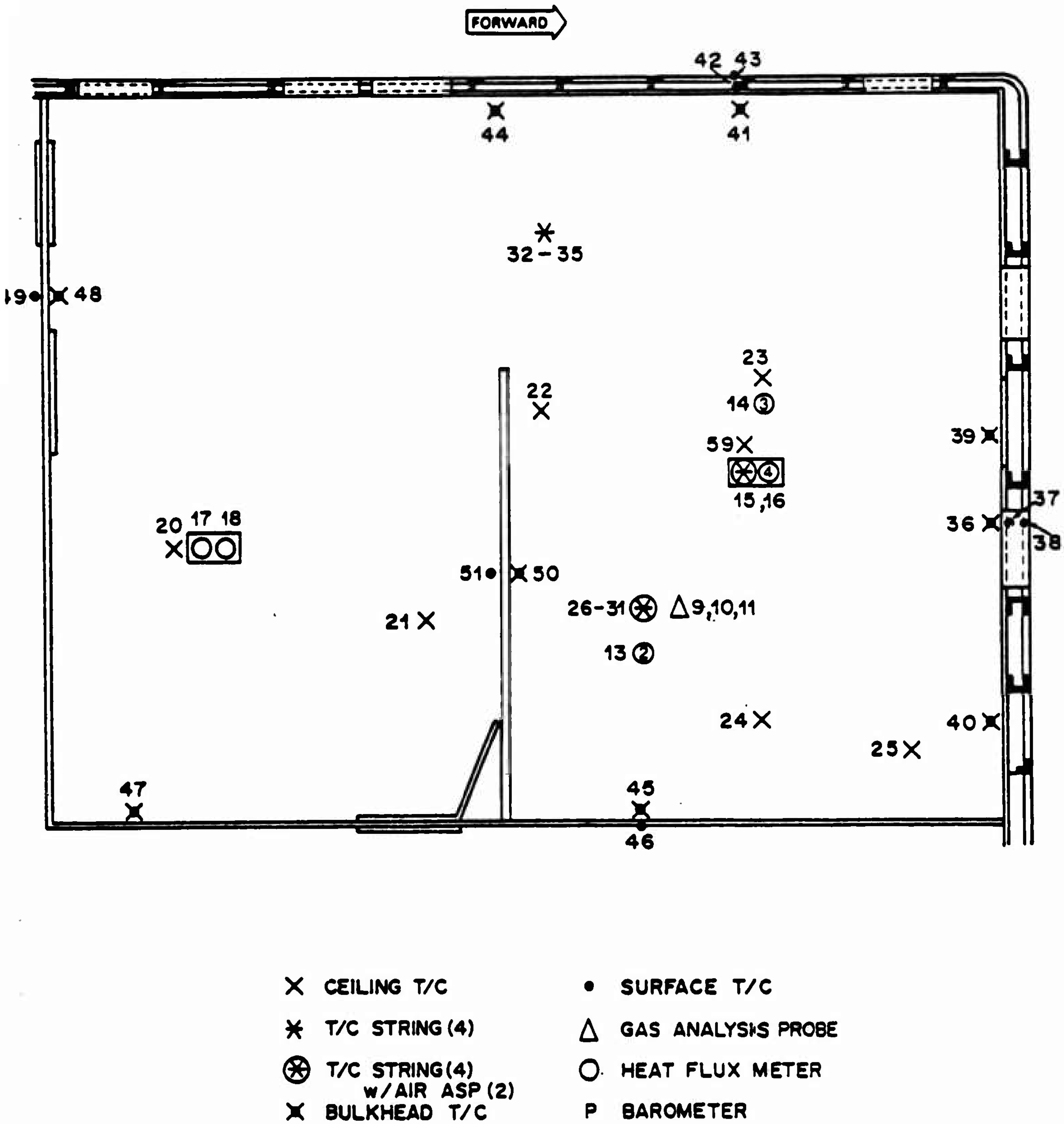


FIGURE 12A. Lounge Plan Showing Instrument Locations for Burnouts 1 and 2

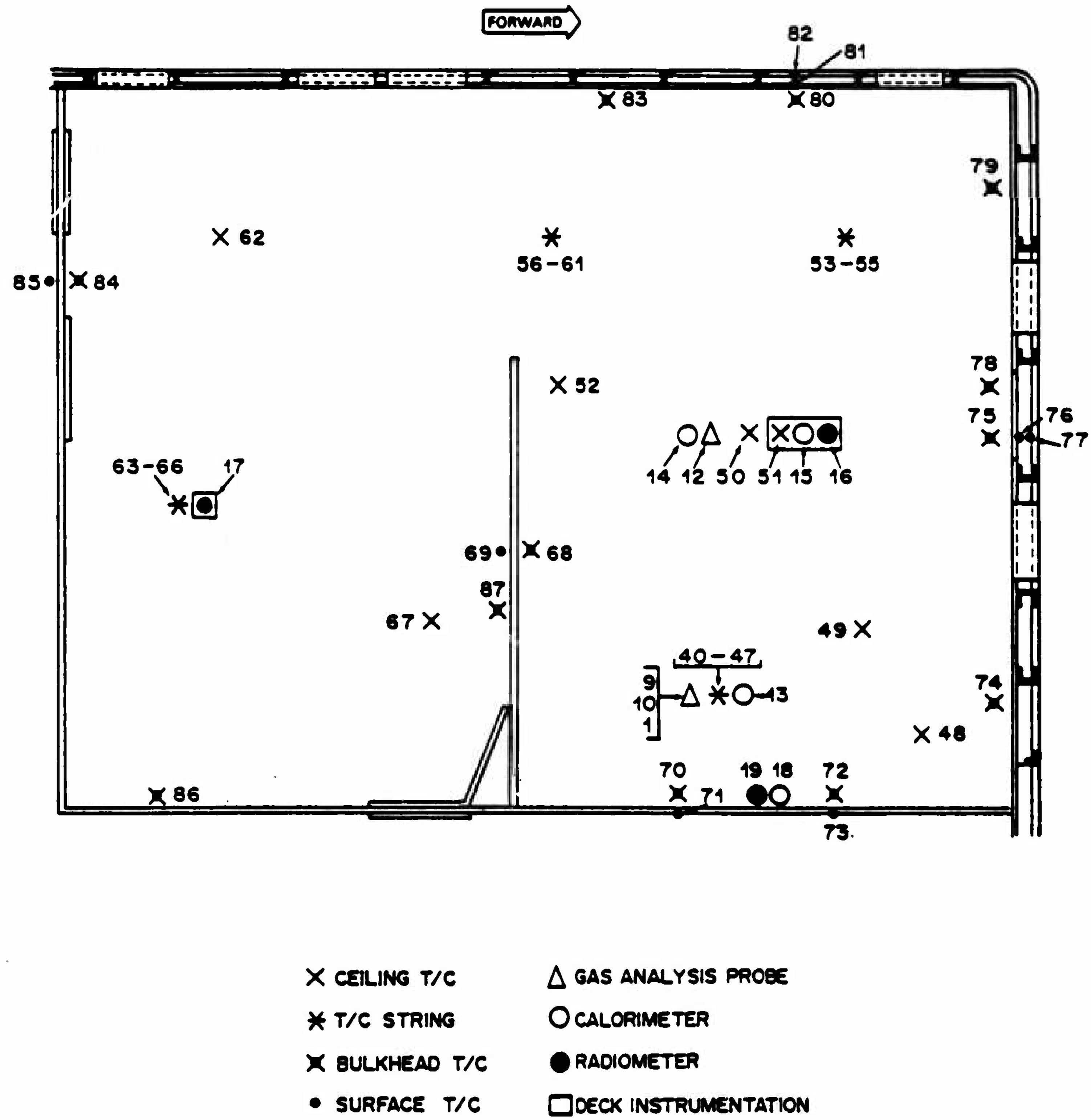


FIGURE 12B. Lounge Plan Showing Instrument Locations for Burnouts 3 through 6

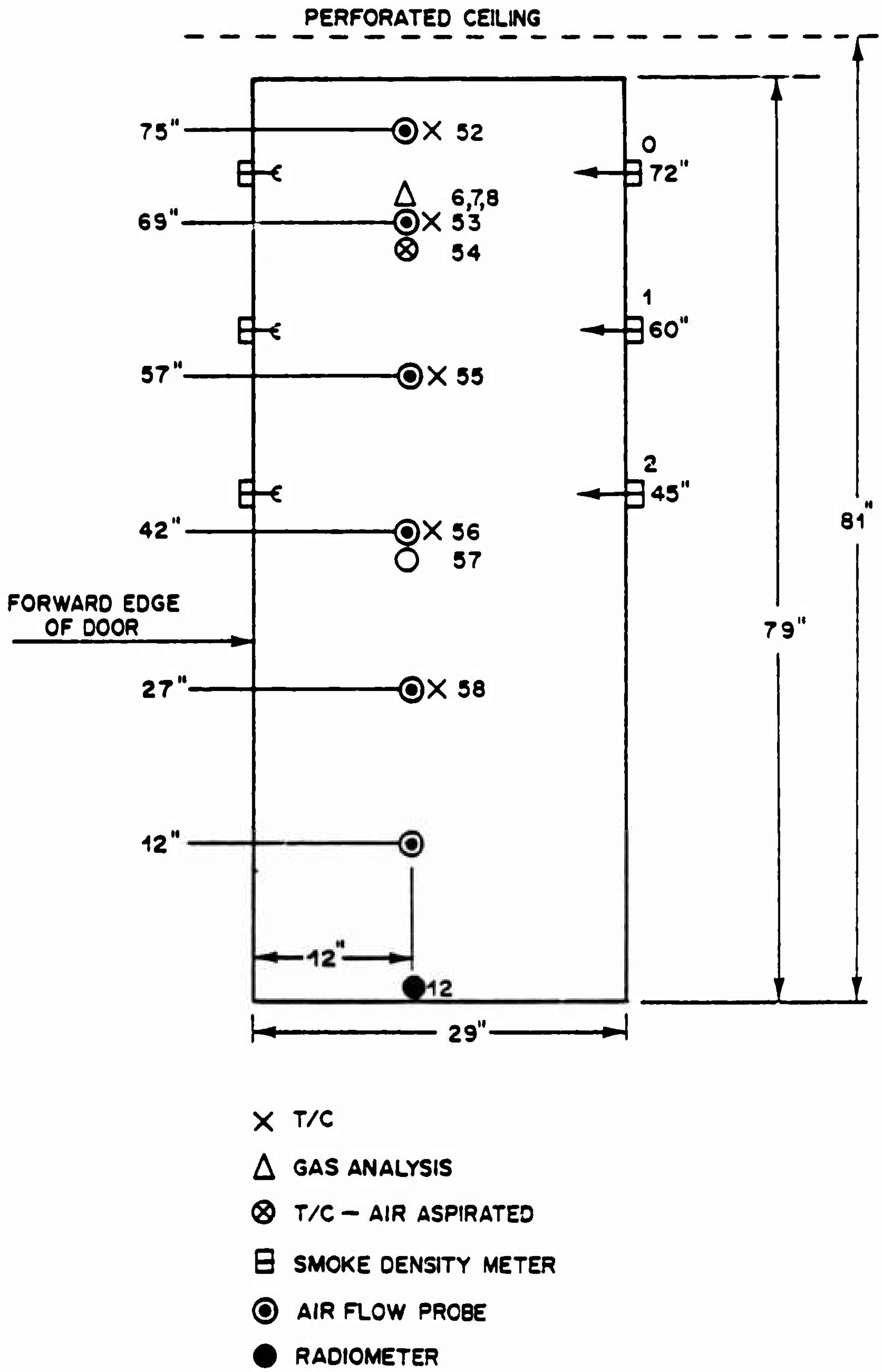


FIGURE 13A. Doorway Instrumentation for Burnouts 1 and 2

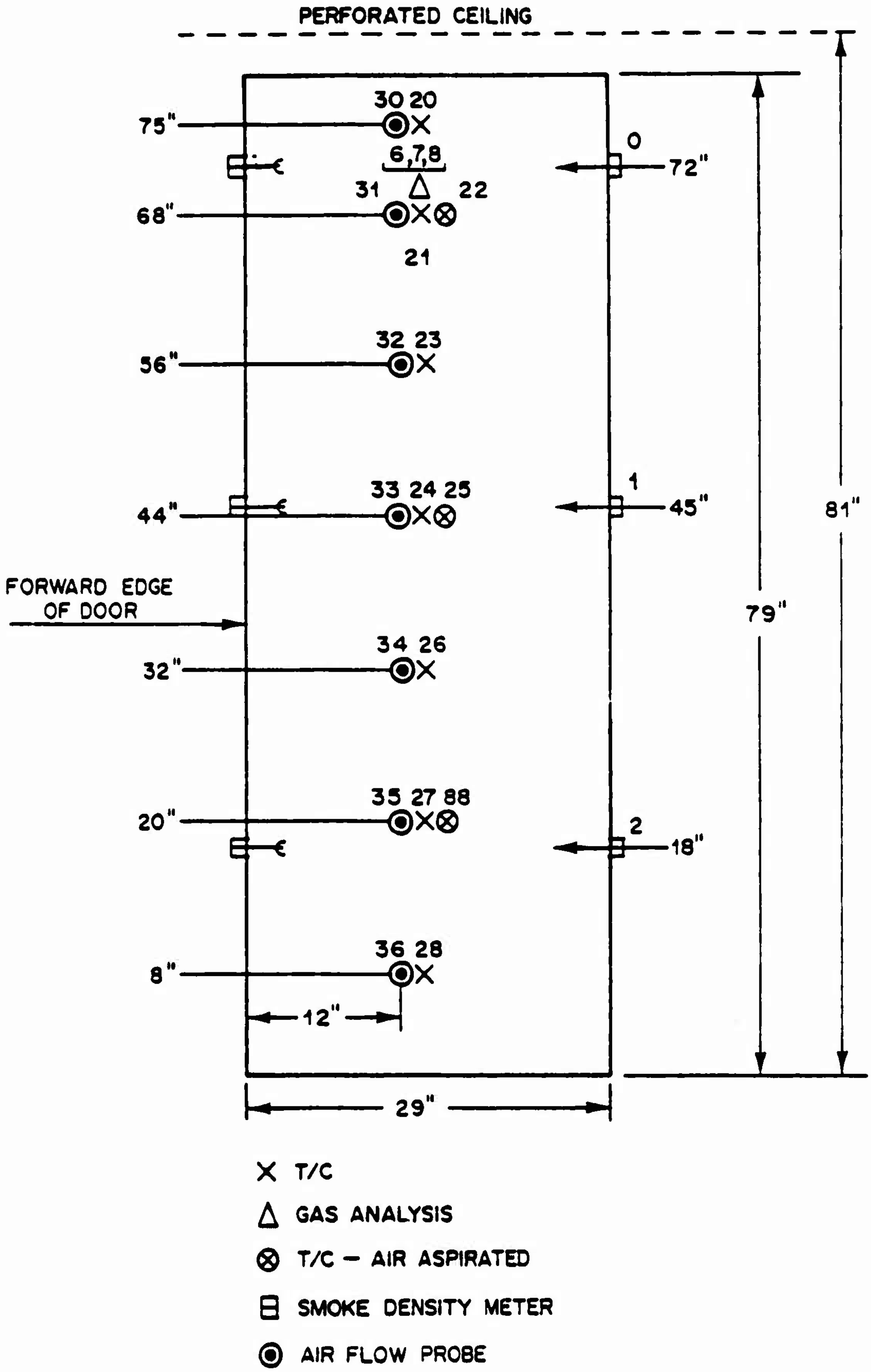


FIGURE 13B. Doorway Instrumentation for Burnouts 3 through 6

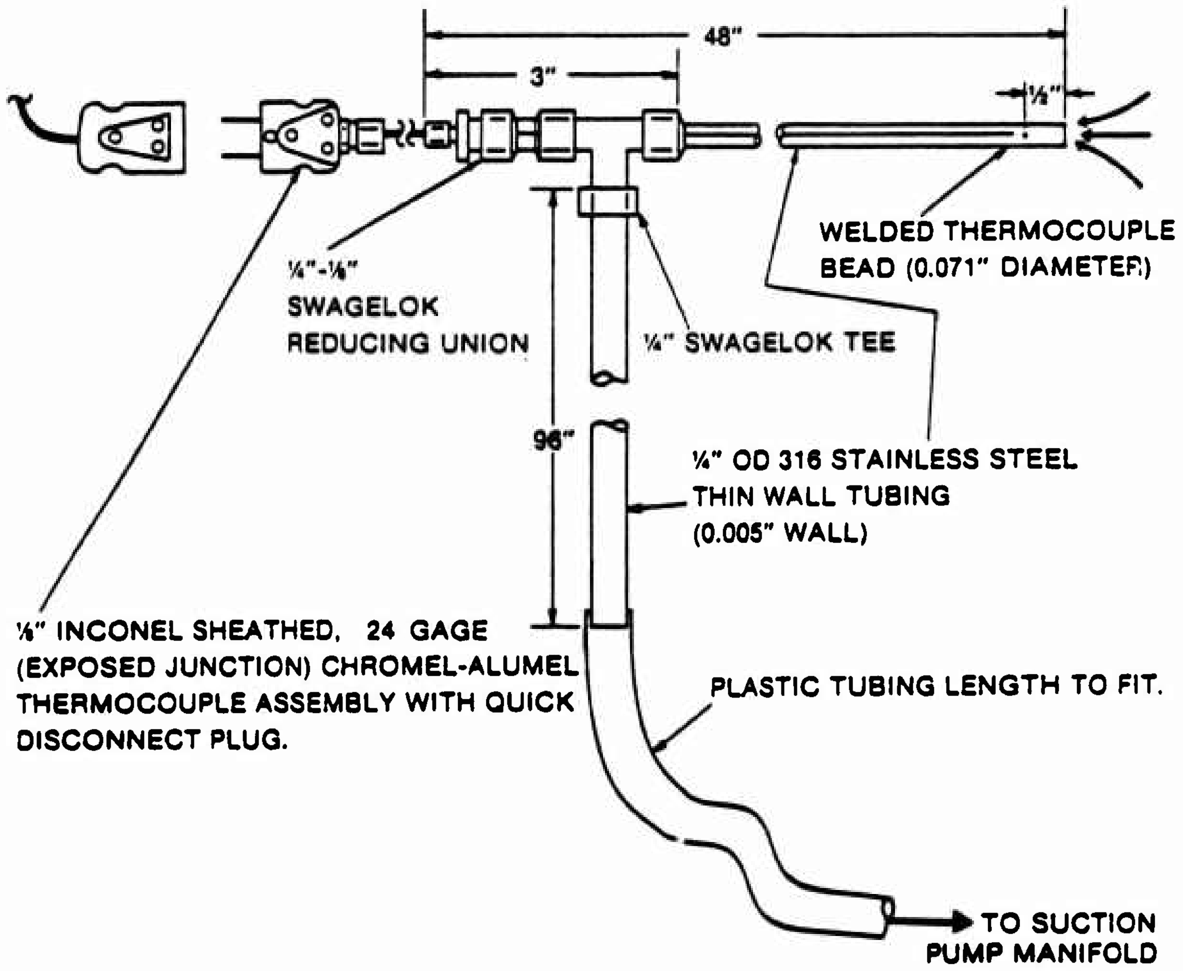


FIGURE 14. Air Aspirated Thermocouple Assembly

The optical density meters were calibrated by interrupting the light beam with calibrated neutral density filters. Calibration points included 0 (100% transmission), 0.2, 0.4, 1.0, 2.0 and 3.0 optical density filters. The logarithm of the output was linear with respect to the optical density to within $\pm$ 0.2 millivolts up to an optical density of approximately 2.4. Measurements above this optical density were of no practical significance.

The output of the meters was in the range of 0 to 100 millivolts which corresponds to 0 to 100 percent light transmission. For reporting purposes, the data was corrected and converted to percent smoke obscuration via the following equations:

$$\% \text{ Smoke Obscuration} = 100 - \text{Percent Light Transmitted}$$

$$= 100 - 100\ ((S - S_0)/(S_{100} - S_0))$$

where S = Output signal in millivolts for the data point
S_0 = Output signal in millivolts with an opaque card blocking the light path
S_{100} = Output signal in millivolts with nothing blocking the light path

3.8.3 Air Velocity

Air velocity was measured at six heights (5 levels for Burnout 1) in the center of the doorway as shown in figure 13 and in the ventilation duct for Burnouts 3 through 6. It was measured with bidirectional low-velocity flow probes[8], each with an outside diameter of 0.875 inch, an inside diameter of 0.750 inch, and a length of 1.750 inches. The probes were oriented directly into the room (i.e., perpendicular to the plane of the doorway). They were connected to differential pressure transducers (Range: $\pm$1 inch of water) by stainless steel and copper tubing. The output of the transducers was fed to a carrier-demodulator which has an output of $\pm$10 volts direct current that was recorded via the data logger. The entire system was calibrated with a small pressure generating bellows which provided a known pressure input as measured by a manometer (Range: 0-0.1 inch of water). Thus each volt of output corresponded to 0.01 inch of water pressure. The polarity was arranged so that positive corresponded to air flow into the compartment (air added) and negative to air flow out.

The recorded output of the carrier-demodulators was converted by computer to give air velocity in meters per second for reporting purposes. The output of the probe for large Reynolds number[8] is described by:

$$(2 \ \Delta P/\rho)^{1/2}/V = 1.08$$

where
V = air velocity (meters per second)
ΔP = the pressure differential (kilograms per meter seconds squared)
= the output of the probe x 2.49
ρ = air density (mass per unit volume) = PM_w/RT
P = atmospheric pressure during the test (atmospheres)
M_w = molecular weight of air at sea level (28.97 grams per mole)
R = gas constant (0.0821 liter atmospheres per mole degree Kelvin)
T = temperature of the air (degrees Kelvin)
= $T_c + 273$
T_c = temperature of the air in degrees centigrade as measured by the thermocouple next to each flow probe.

NOTE: In these equations, we have corrected the density for variations due to temperature and not for variations in molecular weight of the air. Thus changes in the composition of the air due to the fire such as water vapor, CO, CO_2, and smoke product increases and O_2 decreases are not considered.

Solving for V:

$$V = \frac{1}{1.08} \left(\frac{2 \quad P \ R \ (T_c + 273)}{P \quad M_w} \right)^{1/2}$$

$$= 0.0697 \left(\frac{P \ (T_c + 273)}{P} \right)^{1/2}$$

The air velocity V is reported in the results section.

3.8.4 Gas Concentrations

Samples of the lounge's atmosphere were continuously drawn from the center of the doorway at a height of 8 inches, from the inner room 10 inches below the ceiling, and from the inner room 20 inches above the carpet's surface. Samples from the first two locations were continuously analyzed for carbon monoxide, carbon dioxide, and oxygen while the sample from the third location was analyzed for oxygen only. The analysis for carbon monoxide and carbon dioxide was performed with luft-type infrared gas analyzers while the analysis for oxygen was performed with thermomagnetic oxygen analyzers.

All analyzers were calibrated with known gas mixtures and a calibration curve was developed for each. This curve was approximated by an eighth order polynomial equation which was then used to convert the reported data to volume percent of the particular gas. Furthermore, a sample of span gas was introduced at each of the sampling locations and time was kept until each analyzer responded to it. Thus the transit times for each analyzing system were determined and the data corrected to reflect concentrations when they actually occurred in the burnout.

3.8.5 Weight Loss

The weight of the sofa and the weights of the two lounge chairs closest to it were continuously measured throughout the burnouts. This was accomplished by suspending these items of furniture from cables which passed through the ceiling and were attached to load cells above. The results are reported as weight in kilograms as a function of time where the weight of the suspension system has been subtracted to correct the data.

3.8.6 Heat Flux

Seven water-cooled Gardon-type heat flux transducers were placed in five locations in the compartments (see figure 12). In two of these locations a radiometer and a calorimeter were paired so that convective and radiant components of the heat flux could be separated. The data was corrected by a calibration constant and converted to watts per square centimeter for reporting.

3.8.7 Visual Documentation

Visual documentation of the burnouts was accomplished with two videotape recording systems and a 35mm still camera. Still pictures were taken of the lounges before ignition, for several seconds immediately after ignition and after each burnout was extinguished. Videotapes were made from a pan of the lounge before ignition, from two stationary video cameras throughout each burnout, and from a pan of the lounge after ignition. These cameras were positioned and lenses were chosen to provide the fields of view shown in figures 32 and 33, 52 and 53, and 70 and 71 found in sections 4.1, 4.2, and 4.3 respectively. They were placed in air-cooled boxes which had ports protected with glass that could withstand a 1600 degree Fahrenheit temperature differential. The output from a date-time generator was supplied to each videotape so that the date, test number, and test time were recorded along with each burnout.

3.9 Experimental Procedures

The procedures for the six lounge burnouts were as similar as possible. For 24 hours prior to the burnout, the lounge was preconditioned at 70 ± 4 degrees Fahrenheit and 30 ± 6 percent relative humidity. All combustibles were weighed and placed in the lounge. Prior to the initiation of each burnout, all instrumentation was calibrated and checked as described in subsection 3.8. The lounges were inspected for arrangement and placement of combustibles, photographs were taken, and the ambient temperature, relative humidity, barometric pressure, wind speed, and wind direction were measured. The entire instrumentation system including the data logger was then run for three to five minutes immediately prior to ignition. This permitted a last-minute check and the recording of background levels for the various instruments. The time was started upon ignition of the milk cartons in the waste can.

The data logging system ran continually throughout the burnouts and for several minutes into the post-extinguishment phase. Extinguishment was accomplished by supplying water to two sprinkler heads (diameter = 0.436 in., pressure = 100 psi, and flow = 57 gpm), one in the inner room and the other in the outer room. The application time varied between 30 and 75 seconds.

After each lounge had been cooled to ambient conditions, a five-minute scan of all instrumentation was made and the calibration of the air flow probes and smoke density meters was checked. A post-burnout inspection was then made, estimates for the percentage of burnout for the entire lounge and each piece of furniture were made, and photographs were taken.

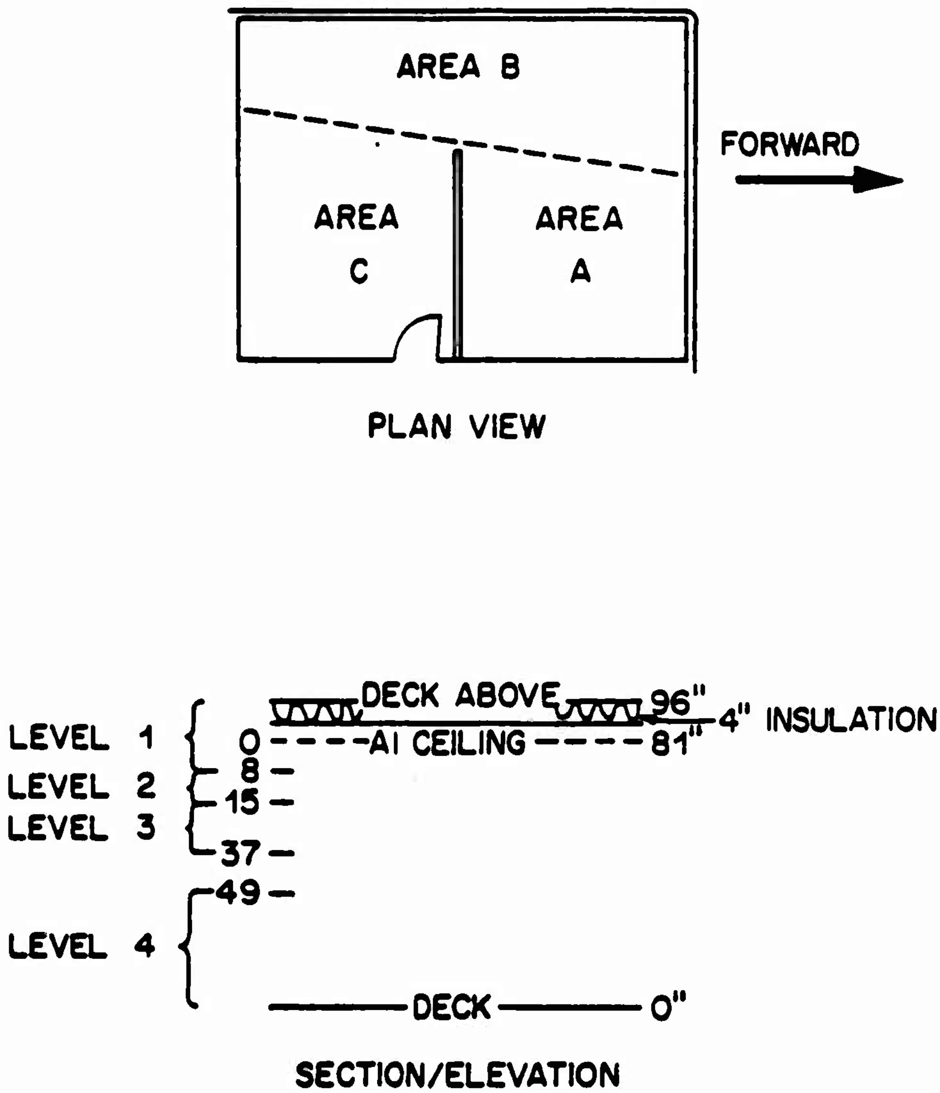
4.0 EXPERIMENTAL RESULTS

The specific observations and measurements taken during the individual burnouts will be reported and discussed in the following subsections. The burnouts are grouped in these subsections according to the type of ventilation that was used. In general, all tests were ignited successfully and were allowed to continue for at least 60 minutes. The wastebasket, filled with milk containers, provided an adequate ignition source. The fire in it, however, was quickly overshadowed by the burning of the sofa. Thus, the ignition source performed its function without providing a significant fire loading of its own.

Fires generally progressed from the wastebasket to the top of the sofa arm, to full involvement of the sofa, to the combustibles and the lamp shade on table 1, to involvement of the carpet and chair 1 and eventually to the entire lounge. Events were observable via the video cameras throughout the duration of the tests when smoke did not obscure their field of view. Initial smoke obscuration occurred between six and eight and one-third minutes into a test. A typical pictorial history of a burnout is shown in figure 15. A log of observations, the extent of damage and the histories of the instrument readings are presented for each experiment. The time of ignition is used as time zero for these histories.

The lounge was divided into three areas for the majority of the temperature analysis. Area A includes the ignition source and the bulk of the inner room. Area B is the transition area between the inner and outer rooms and area C contains the bulk of the volume of the outer room as shown in figure 16. These areas were further divided into horizontal levels. Level 1 includes the volume from the deck above to 8 inches below the suspended ceiling, thus it includes the void space above the ceiling. Level 2 includes the volume from 8 inches below the ceiling to 15 inches below the ceiling, level 3 includes the volume from 15 inches below the ceiling to 37 inches below the ceiling, and level 4 includes the volume from 49 inches below the ceiling to the deck. The thermocouples in the zones defined by these areas and levels are shown in table 4. In reviewing the data, one should be careful when interpreting the readings in area C because of door effects, especially during Burnouts 1 and 2 when there were a limited number of thermocouples in this area. Level 4 will be given very little attention in the discussion because it is very low in the space and thus the worst-case high temperatures are not found there.

FIGURE 15. Pictorial History Of A Lounge Burnout



NOTE: A ZONE IS THE VOLUME DEFINED BY ONE LEVEL IN AN AREA.

FIGURE 16. Zones in Lounge Used for Temperature Analysis

TABLE 4

THERMOCOUPLES LOCATED IN ZONES (SEE FIGURE 16)

ZONE AREA-LEVEL	CHANNEL NUMBER* BURNOUTS 1 AND 2	BURNOUTS 3 THROUGH 6
A-1	22,24,25,26,27,40	40,42,48,49,50,52
A-2	29,45,50	44,68,70,74
A-3	-	45,72
A-4	31	46,72
B-1	23,32,33,44	53,56,62,67
B-2	34,36,41,48	54,58,75,80,83
B-3	39	59,78,79,84
B-4	35	55,60,61
C-1	20,21	63,64,67
C-2	-	65,69,87
C-3	47	33,34,86
C-4	-	36,39,66

*See Appendix B for locations.

4.1 Results of Burnouts with Closed Ventilation (Burnouts 1 and 2)

The ventilation ducts in the overhead of the inner and outer rooms were closed for these tests. The burnouts progressed in a similar manner. Flames reached the top of the sofa arm, the sofa vinyl caught fire, and initial smoke obscuration occurred at approximately the same times for each test (see tables 5 and 6). Each test had three temperature peaks as seen in figures 17, 18, 25 and 26. In both cases, the first peak exceeded the ASTM E119 time-temperature curve. The first and last peak were 27 minutes apart in Burnout 1 but only 19 minutes apart in Burnout 2. The maximum heat fluxes in the inner rooms (figures 19 and 27) correspond with the temperature peaks for both tests. Oxygen concentration valleys and carbon monoxide and carbon dioxide peaks (see figures 20 and 28) followed these temperature peaks by a few minutes. The weight loss histories for the sofa and chairs 1 and 2 are not shown for Burnout 1 because the suspension systems failed and for Burnout 2 because the calibration of the load cells was inaccurate.

The average temperatures in the doorways (figures 21 and 29) peaked one to two minutes after the corresponding temperature peaks in the inner rooms and were much cooler as would be expected. Smoke obscuration as measured in the doorways reached 100 percent 7.5 and 7.0 minutes after ignition in Burnouts 1 and 2 respectively (see figures 22 and 30). This occurred approximately one minute earlier than the inner room was thought to be smoke obscured (tables 5 and 6) as determined by observation of the video tapes. The flow of fire gases reported as air velocity (figure 23 for Burnout 1) was out of the lounge in the upper two thirds of the doorway and into the compartment in the lower third. "Breathing" of the fire is illustrated by the measurement taken at the height of 1.07 meters. Each outflow of fire gases was followed by momentarily increased fresh air inflow. A brief shift between outflow and inflow occurs here for each peak in the temperature histories. Air velocity is not reported for Burnout 2 because of failure of the instruments. Oxygen, carbon monoxide, and carbon dioxide concentration histories in the doorway (figures 24 and 31) were very similar to those in the inner rooms. Observations from the video tapes are recorded in tables 5 and 6 and show extensive fire involvement in the inner room and essentially none in the outer room.

The extent of damage is displayed in figure 32 and table 7 for Burnout 1 and figure 33 and table 8 for Burnout 2. The area which was totally burned out was limited to the portion of the inner room containing the sofa, endtable 1, chair 1 and endtable 3 in both tests. Lines of demarcation of the fires' progress were evident in the carpets. The partial burnouts could have been caused by either the limited ventilation, high moisture contents due to rain prior to the tests or a combination of the two. The carpet was not burnt under the coffee table. Since the carpet was burnt all around the coffee table, one would assume that the carpet's contribution to fire growth in the room was not as significant as the radiant heat from above. Chairs 2 and 3 located outside this area were partially burnt again because of radiant heat. The Marinite panels remained intact with one slight crack in the corner by endtable 1 in Burnout 2. The plastic laminate peeled off all panels in the inner room and several panels in the outer room. As it peeled off it burned and contributed to the fire. The ceiling material was weakened and distorted by the fire to the point where the stream from a fire hose knocked most of it down during cleanup operations.

TABLE 5

LOG OF OBSERVATIONS FROM BURNOUT 1 (CLOSED VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition in waste basket
00:30	Flames above top of waste basket
00:50	Flames to top of sofa arm
01:00	Vinyl on sofa caught fire
01:14	Flames to top of sofa back
02:00	Vinyl on side and top of sofa arm burning
02:55	Vinyl on top of sofa back burning
03:10	Top 1/3 of inner room smoke obscured.
04:12	Flames 1.5 ft above sofa back at starboard end
04:36	Burning plastic falling from sofa
05:07	Newspaper on left side of sofa caught fire
06:00	Flames within 1.0 ft of ceiling
06:12	Newspaper on left side of sofa totally involved
07:03	1/3 of surface area of sofa burning
08:40	Inner compartment smoke obscured
12:35	Fire ball swept across ceiling
12:48	Fire at lower right - probably chair 1 burning
13:20	Fire at lower right died out
15:30	Fire seen through smoke at lower right
18:00	Open flames at lower right
20:40	Entire right side burning (magazine stand/chair 1)
20:45	Video tape ends
21:55	New video tape begins - right side still burning
22:50	Entire screen filled with flames
25:10	Flames died out
57:00	Sprinklers turned on in compartment

TABLE 6

LOG OF OBSERVATIONS FROM BURNOUT 2 (CLOSED VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition in waste basket
00:33	Flames above top of waste basket
01:38	Flames to height of sofa arm
02:24	Sofa vinyl caught fire - smoke became darker
03:26	Burning plastic falling from sofa - small pieces
03:41	Flames to top of sofa at port end
06:28	Flames moving across sofa back
06:38	Instrumented doorway in outer room totally smoke obscured
06:48	Burning plastic falling from sofa back - large pieces. Carpet beginning to burn
07:11	Fire jumped to lampshade 1
07:35	Fire jumped to newspapers below lampshade 1
08:08	Inner compartment obscured by smoke - no visible flame. Audible heavy burning continues
11:00	Glow of fire in forward port corner
11:08	Fire flared up in forward port corner
24:00	Forward port corner, i.e., chair 1, fire alternately glows and becomes obscured by smoke
24:13	Flame from burning coffee table visible and growing
28:00	Flames from carpet immediately in front of camera obscure coffee table flames
31:00	Flames from coffee table still visible then die out
32:00	Flames occasionally slightly visible through smoke - audible crackle from fire through remainder of test
68:23	Sprinklers turned on in compartment

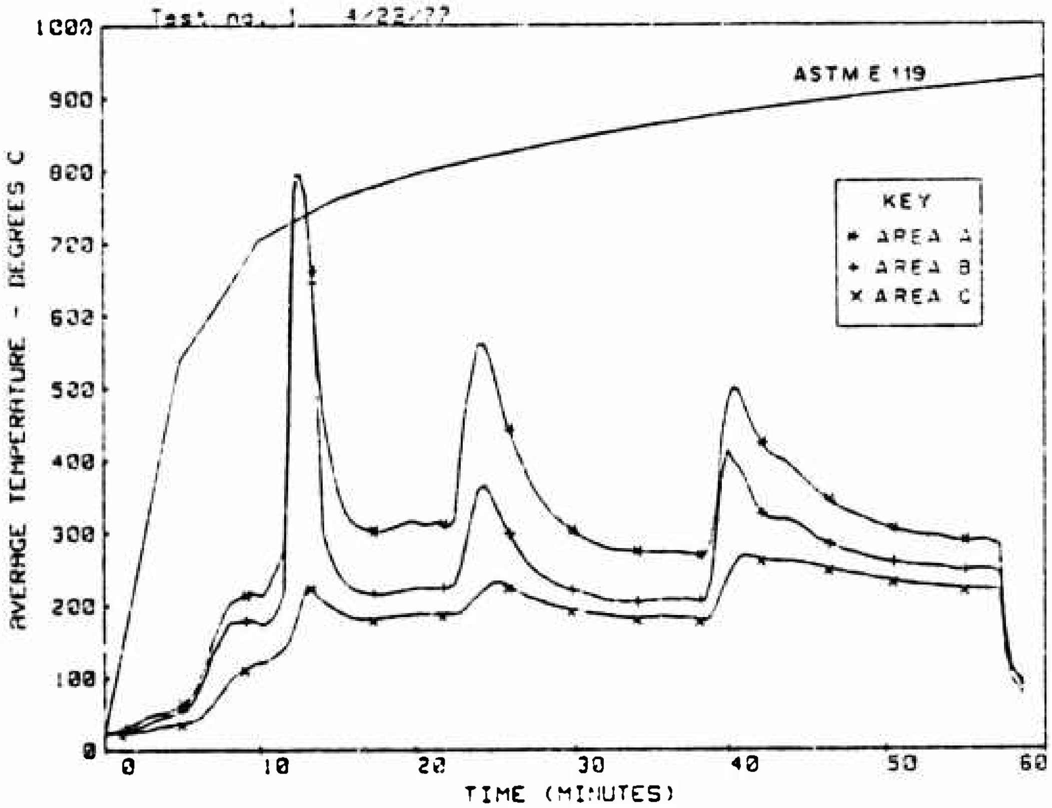


FIGURE 17. Average Upper (Level 1) Gas Temperature Histories for Burnout 1

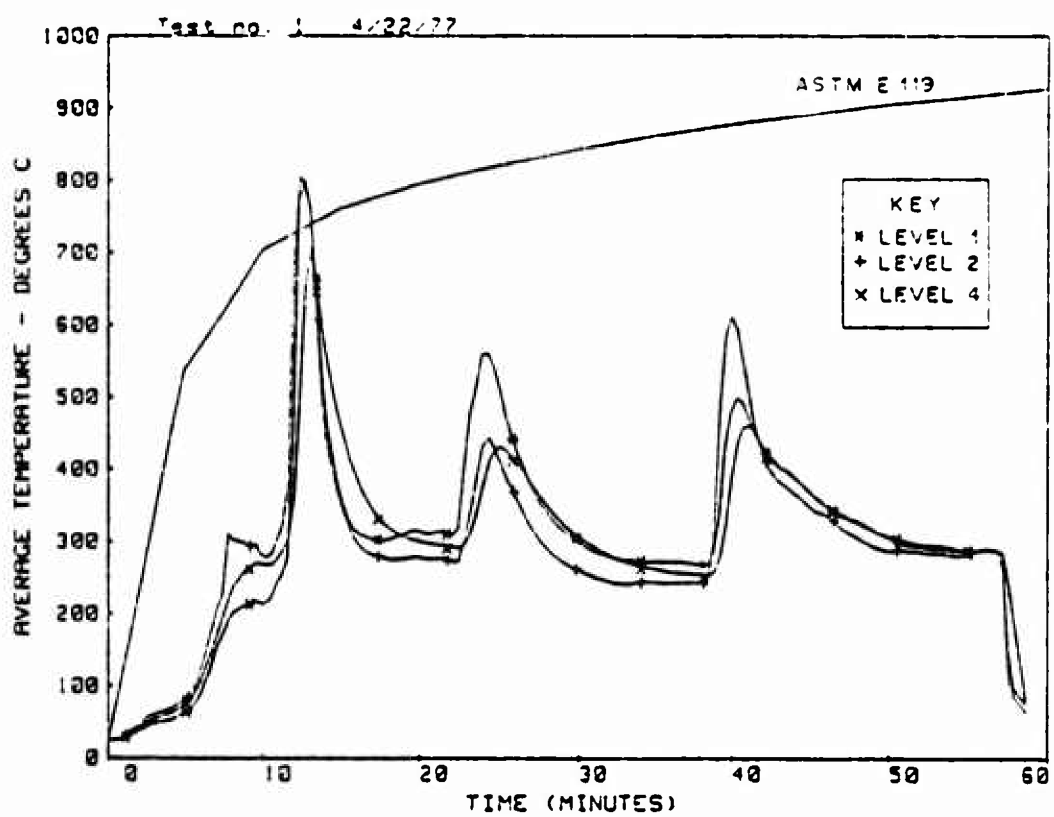


FIGURE 18. Average Inner Room (Area A) Gas Temperature Histories for Burnout 1

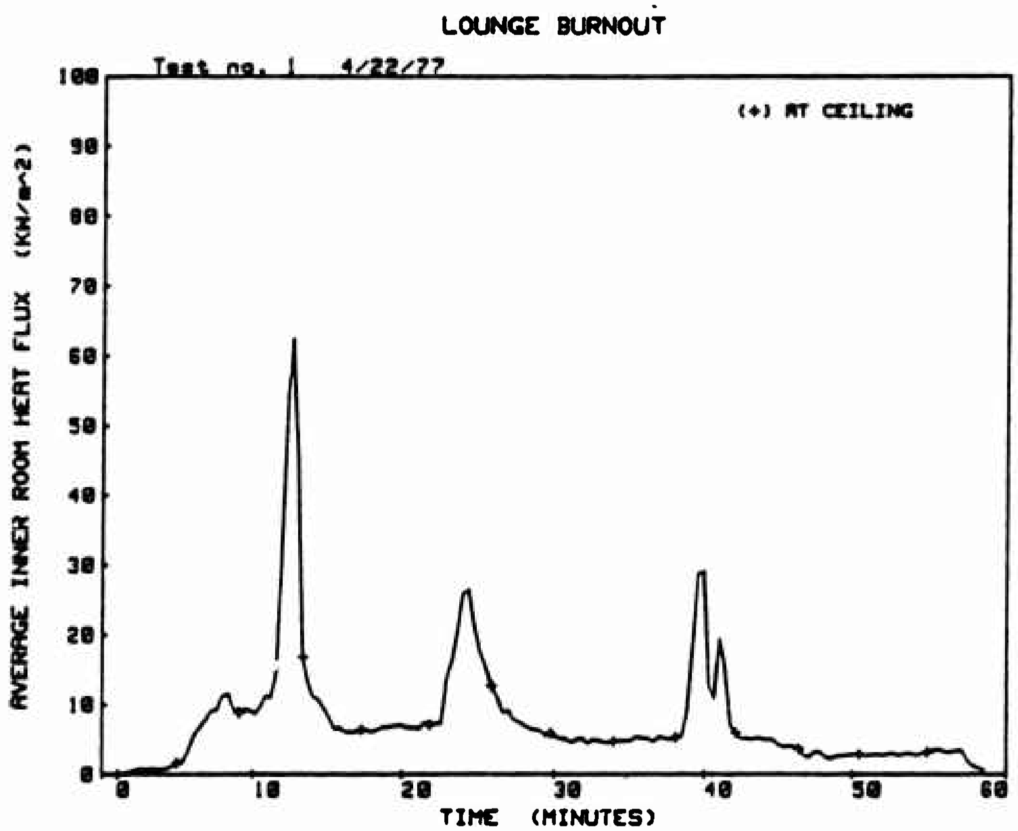


FIGURE 19. Average Inner Room Heat Flux History for Burnout 1

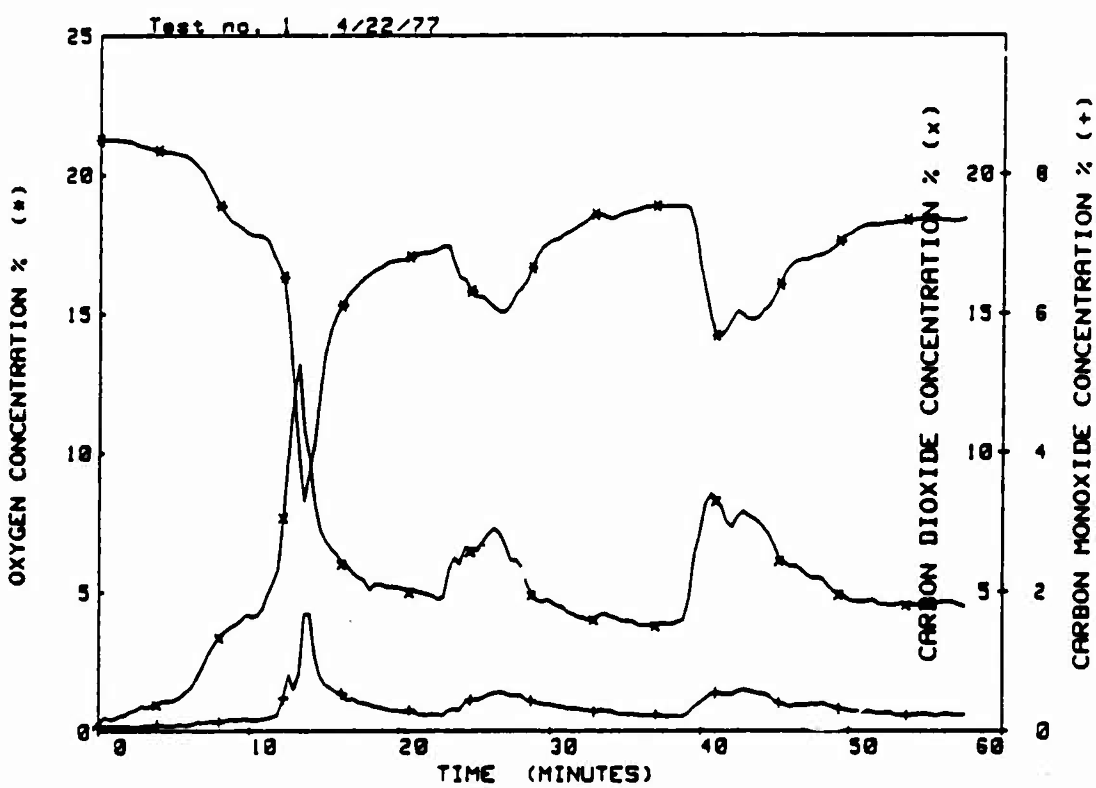


FIGURE 20. Inner Room Gas Concentration Histories for Burnout 1

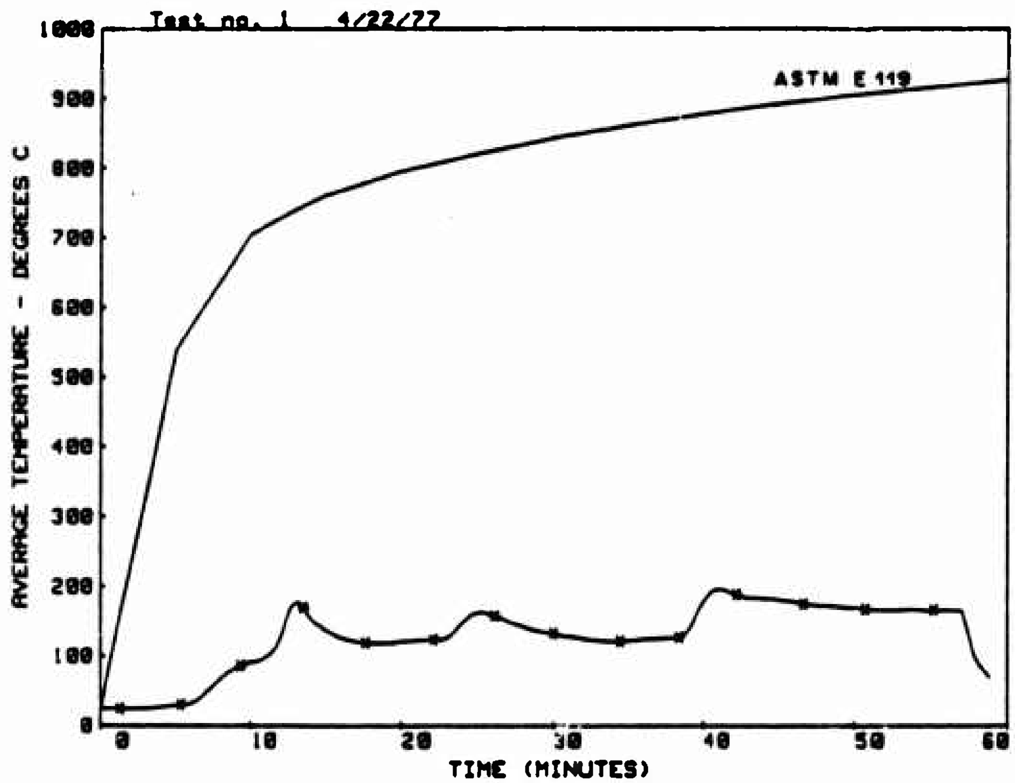


FIGURE 21. Average Doorway Temperature History for Burnout 1

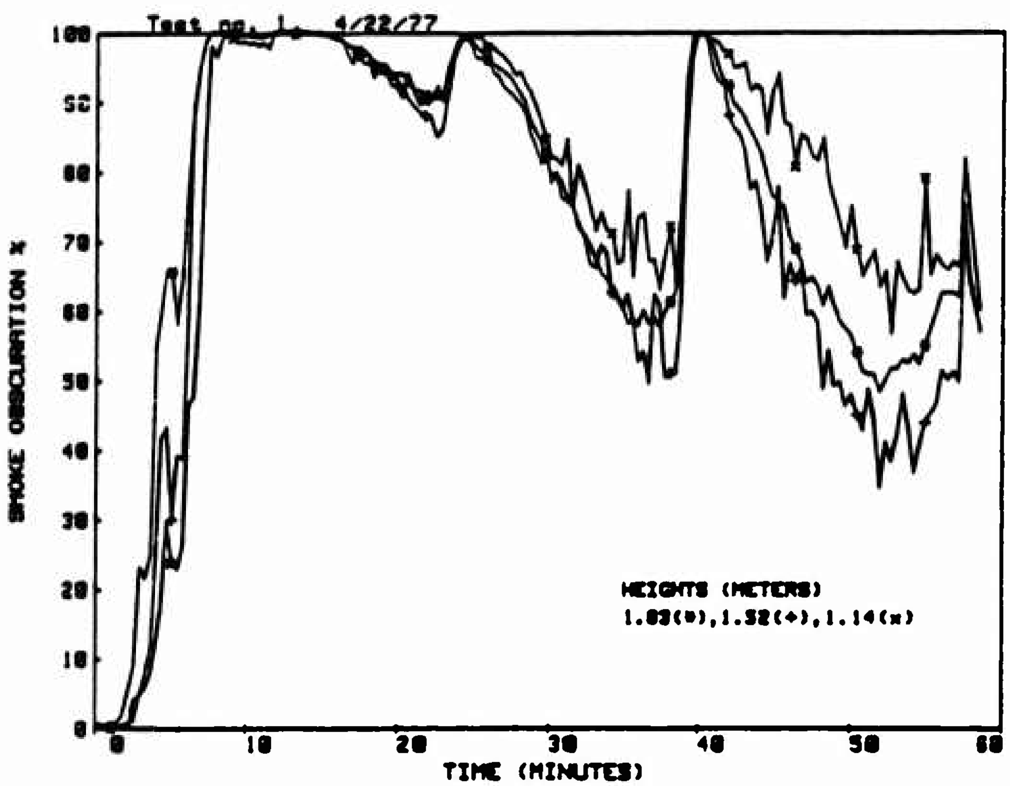


FIGURE 22. Smoke Obscuration Histories in Doorway for Burnout 1

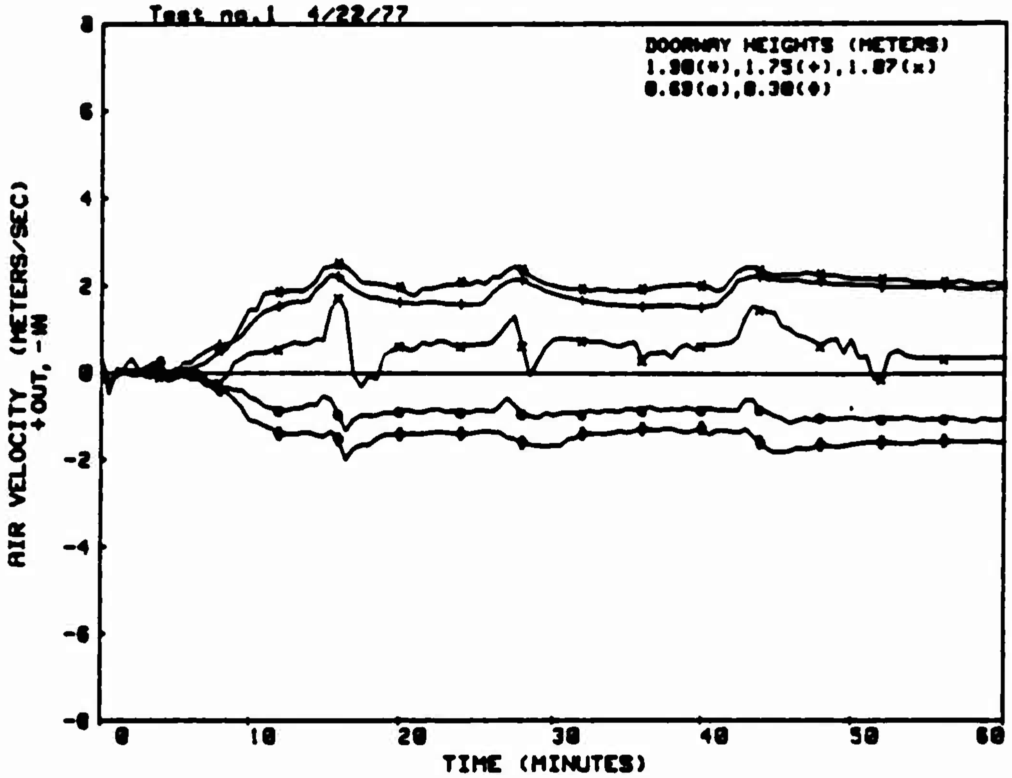


FIGURE 23. Air Velocity Histories Through Doorway for Burnout 1

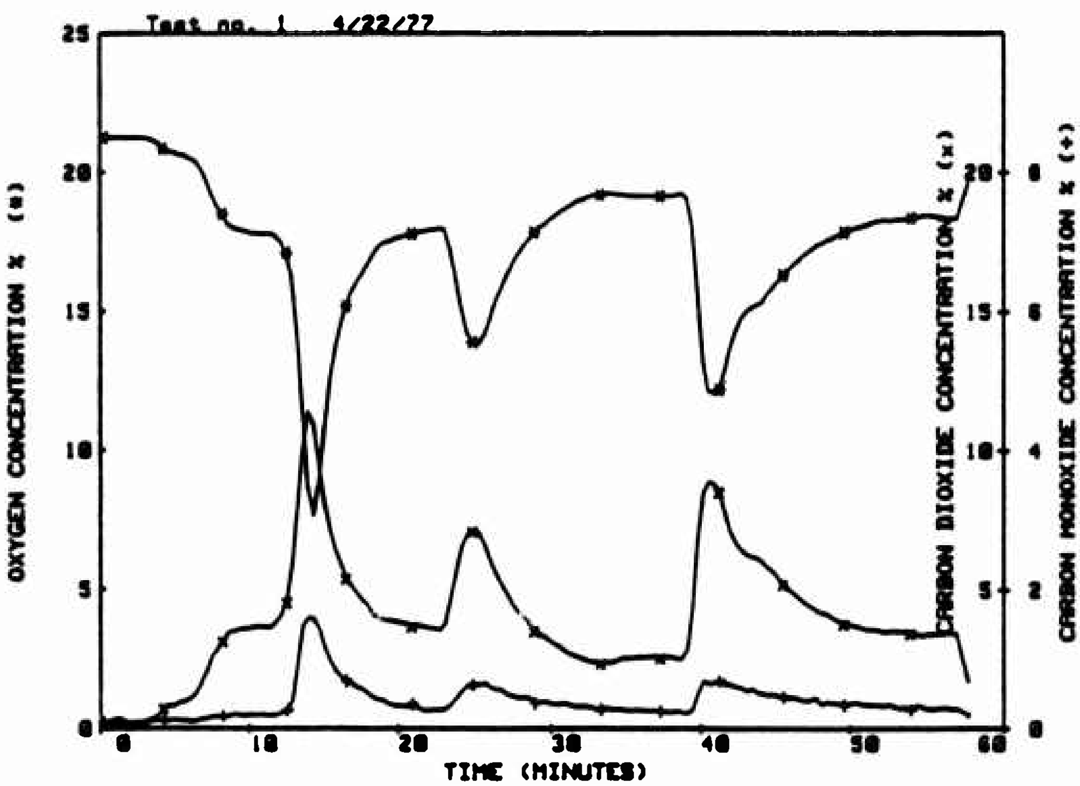


FIGURE 24. Doorway Gas Concentration Histories for Burnout 1

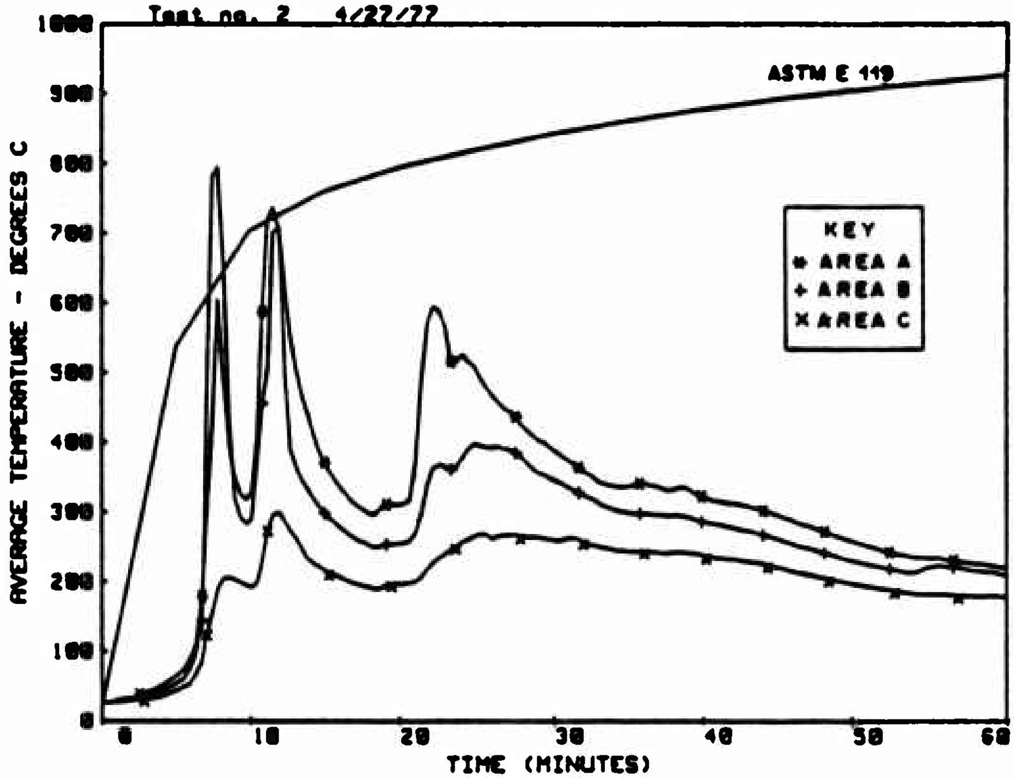


FIGURE 25. Average Upper (Level 1) Gas Temperature Histories for Burnout 2

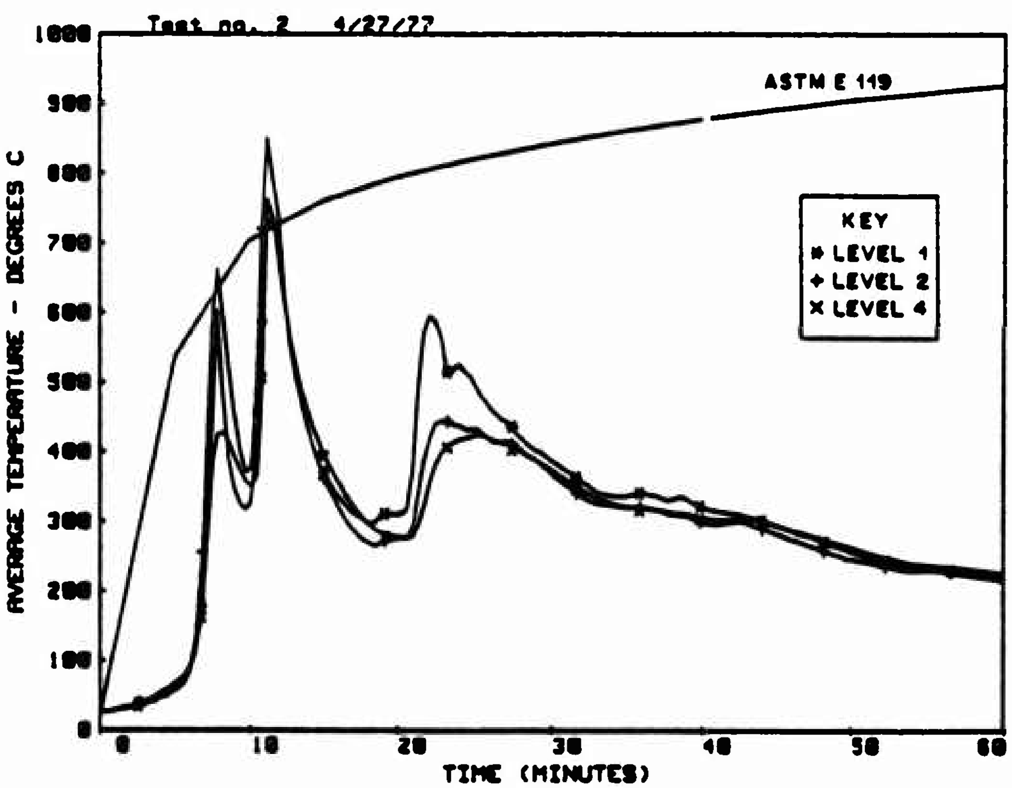


Figure 26. Average Inner Room (Area A) Gas Temperature Histories for Burnout 2

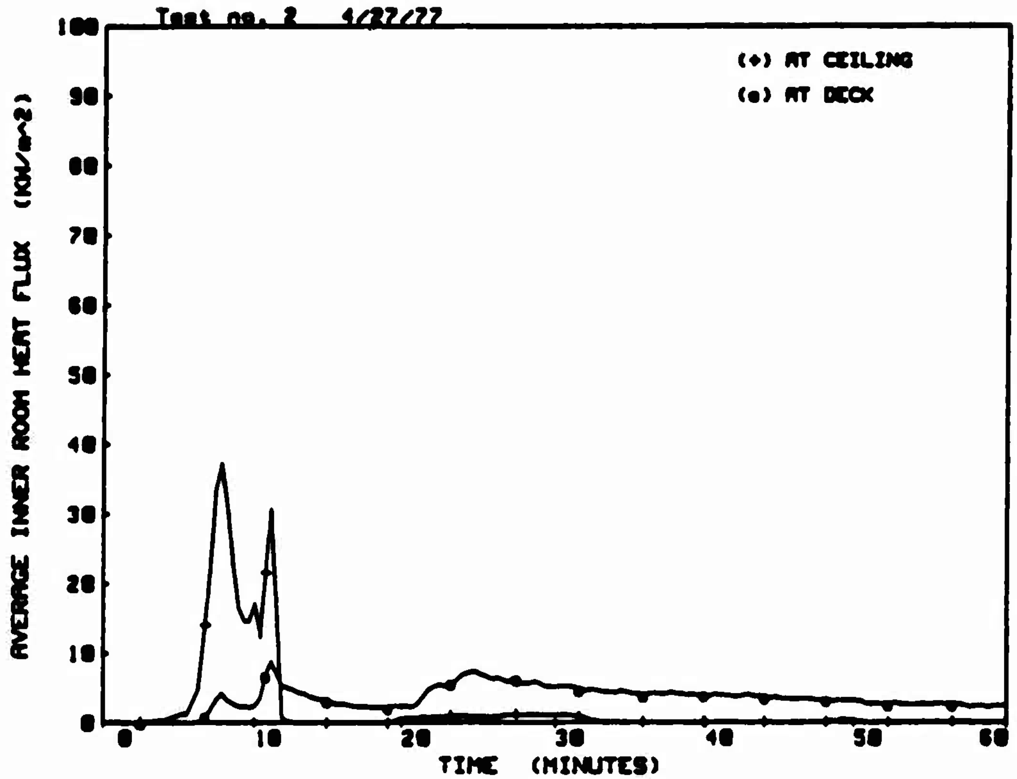


FIGURE 27. Average Inner Room Heat Flux Histories for Burnout 2

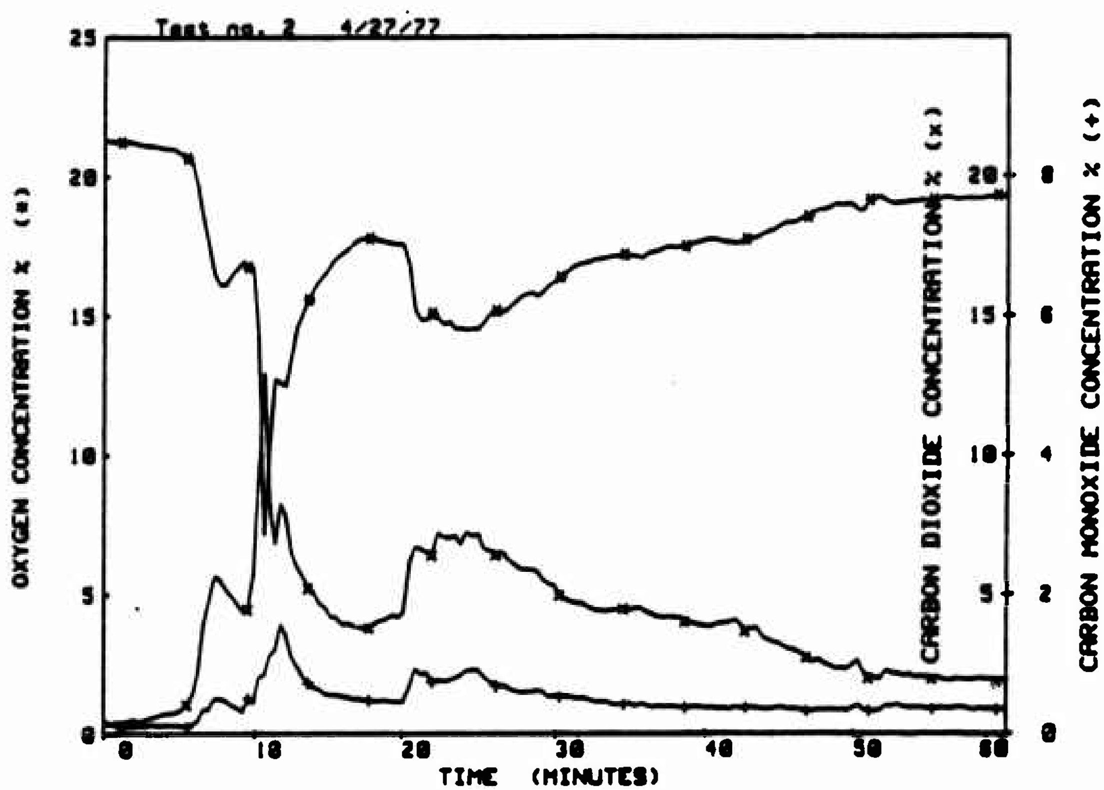


FIGURE 28. Inner Room Gas Concentration Histories for Burnout 2

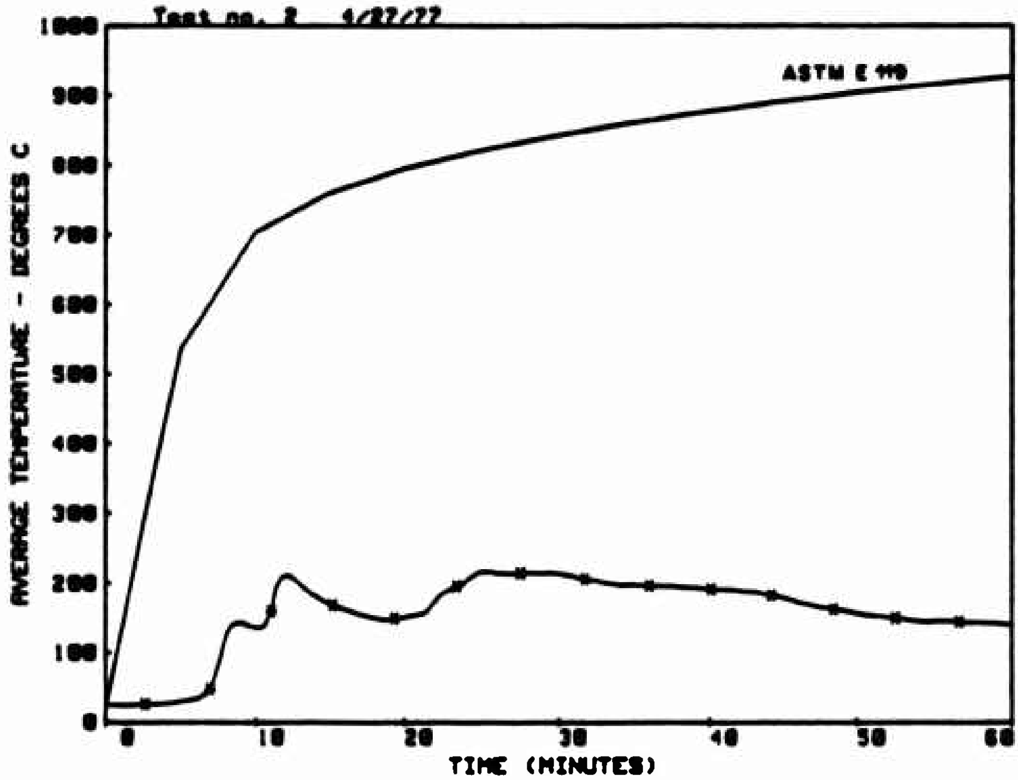


FIGURE 29. Average Doorway Temperature History for Burnout 2

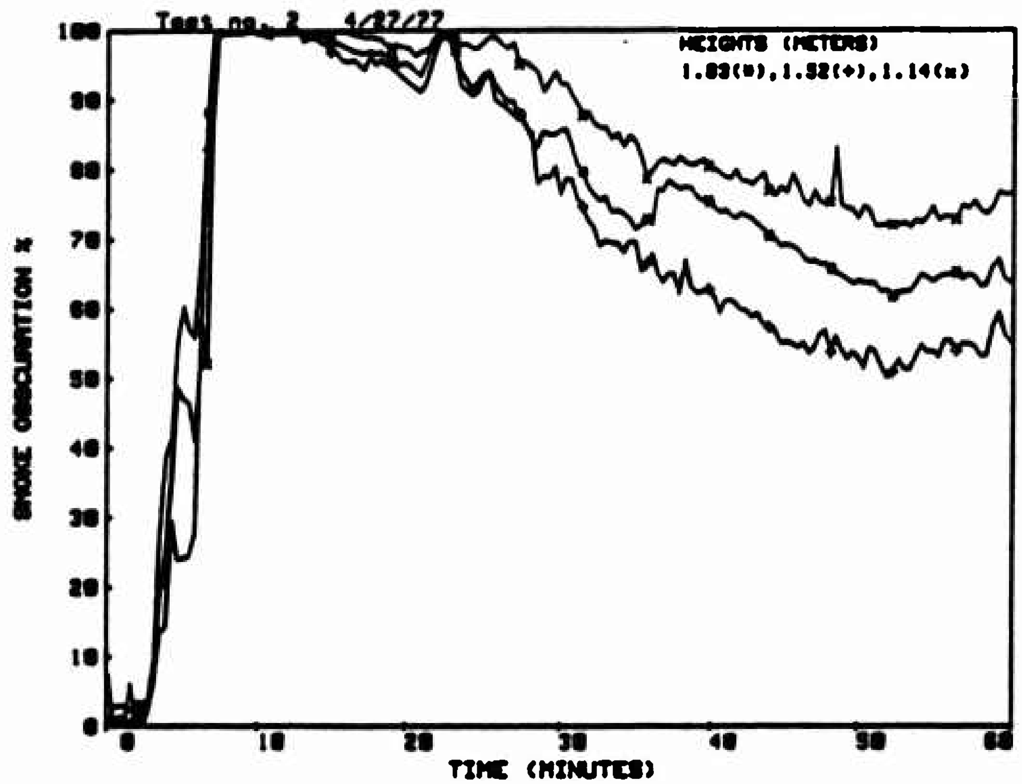


FIGURE 30. Smoke Obscuration Histories in Doorway for Burnout 2

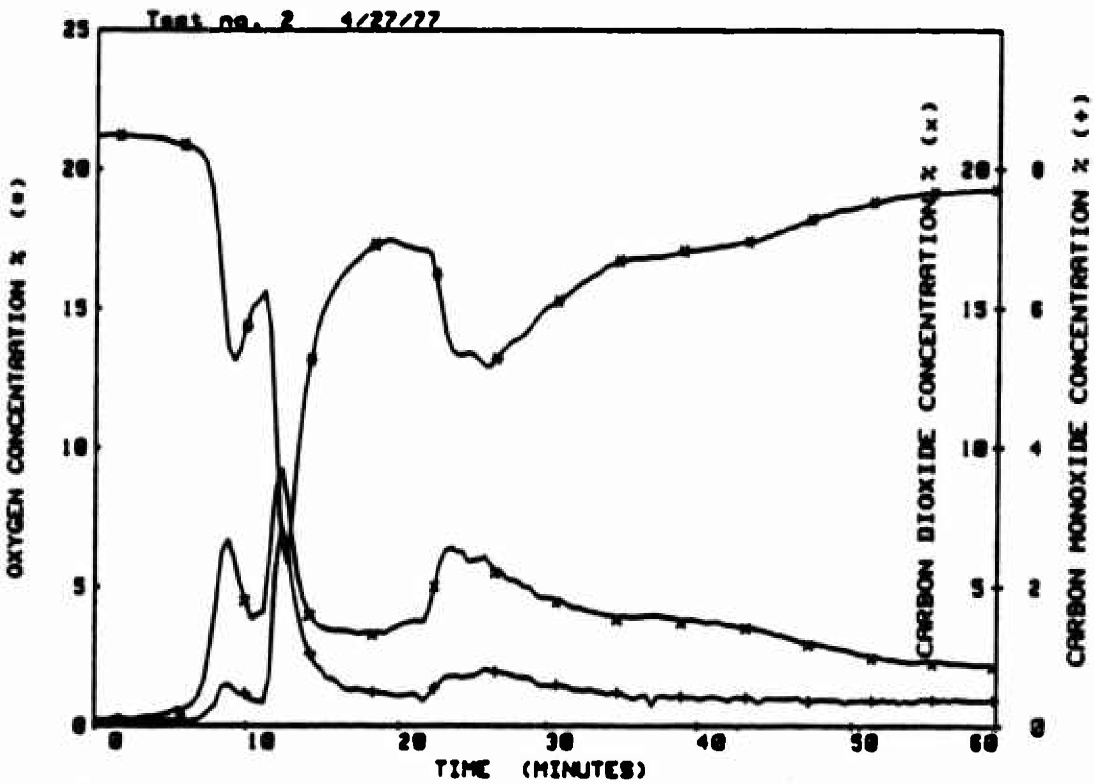


FIGURE 31. Doorway Gas Concentration Histories for Burnout 2

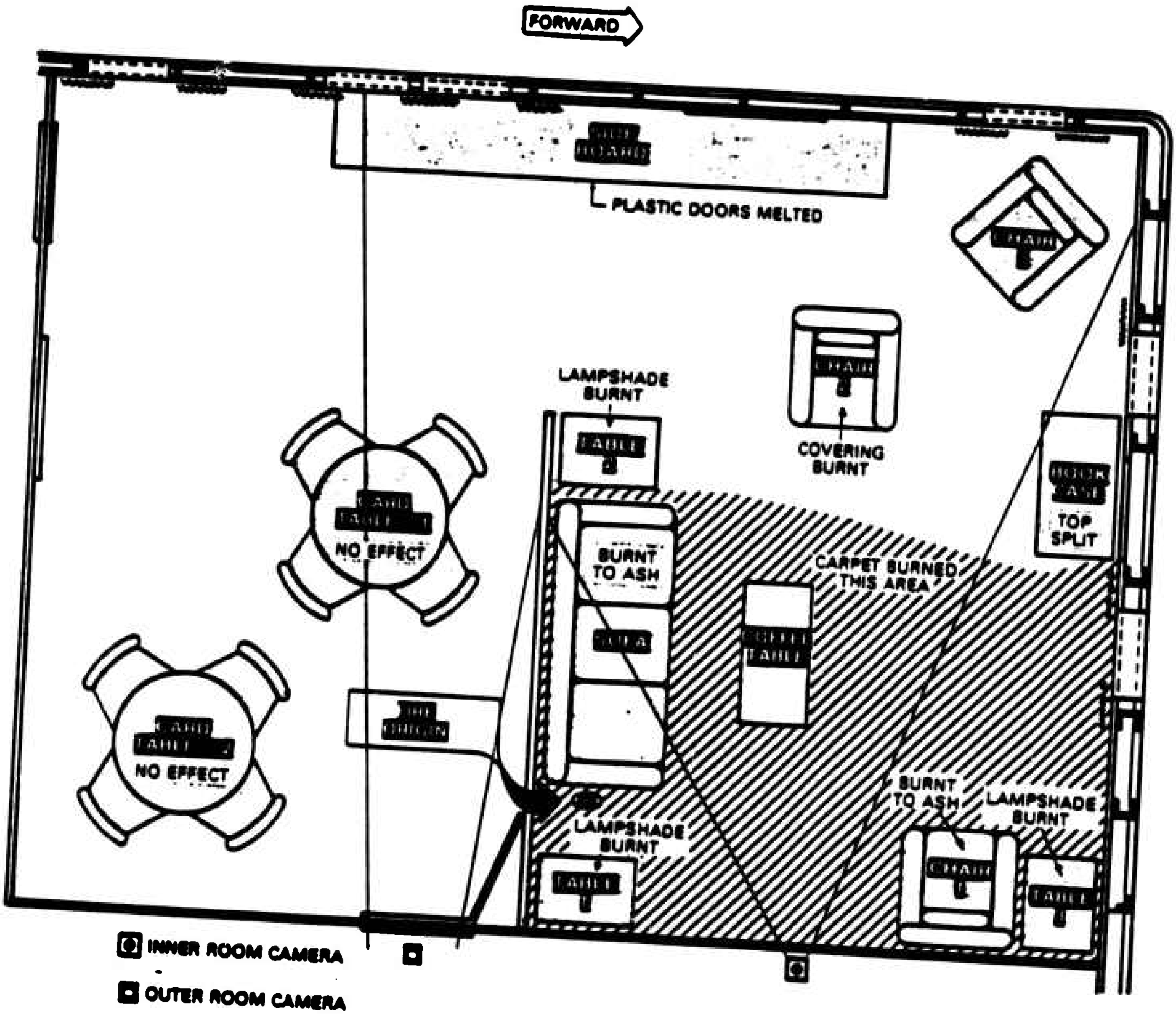


FIGURE 32. Extent of Damage for Burnout 1

TABLE 7

EXTENT OF FIRE DAMAGE FOR BURNOUT 1 (CLOSED VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Lamp shades burnt off
Table & lamp 2	Lamp shades burnt off
Table & lamp 3	Lamp shades burnt off
Chair 1	Totally burnt
Chair 2	Vinyl burnt - urethane foam burnt very little
Chair 3	Not burnt
Coffee table	Laminate came off and burnt
Bookcase	Top split in thickness - magazines on top burnt
Sideboard	Plastic doors warped and slightly melted; charring of contents
Carpet and pad	Burnt in sofa/chair one-half of inner room (see below)
Curtains	Material not burnt - thread melted out
Wall covering	Came off in sheets and burned - many lower portions not affected
Wall base	No effect
Tracking system	Remained intact - no warping
Ceiling material	Broke into pieces - knocked down by hose stream over sofa/chair area
Light diffusers	Warped two near sofa; 75% melted
Combustibles	Foam cups burnt - paper in waste baskets not burnt
Outer Room	
Card tables	No effect
Steel chairs	Slight melting of vinyl
Aluminum chairs	No effect
Bulletin boards	Did not burn
Carpet	Did not burn
Wall covering	Came off joiner bulkhead and burned
Wall base	No effect
Tracking system	Remained intact - no warping
Ceiling material	Remained intact
Light diffusers	Warped and hanging from fixture
Combustibles	Checkers and chips melted some - cards, cardboard, newspaper did not burn

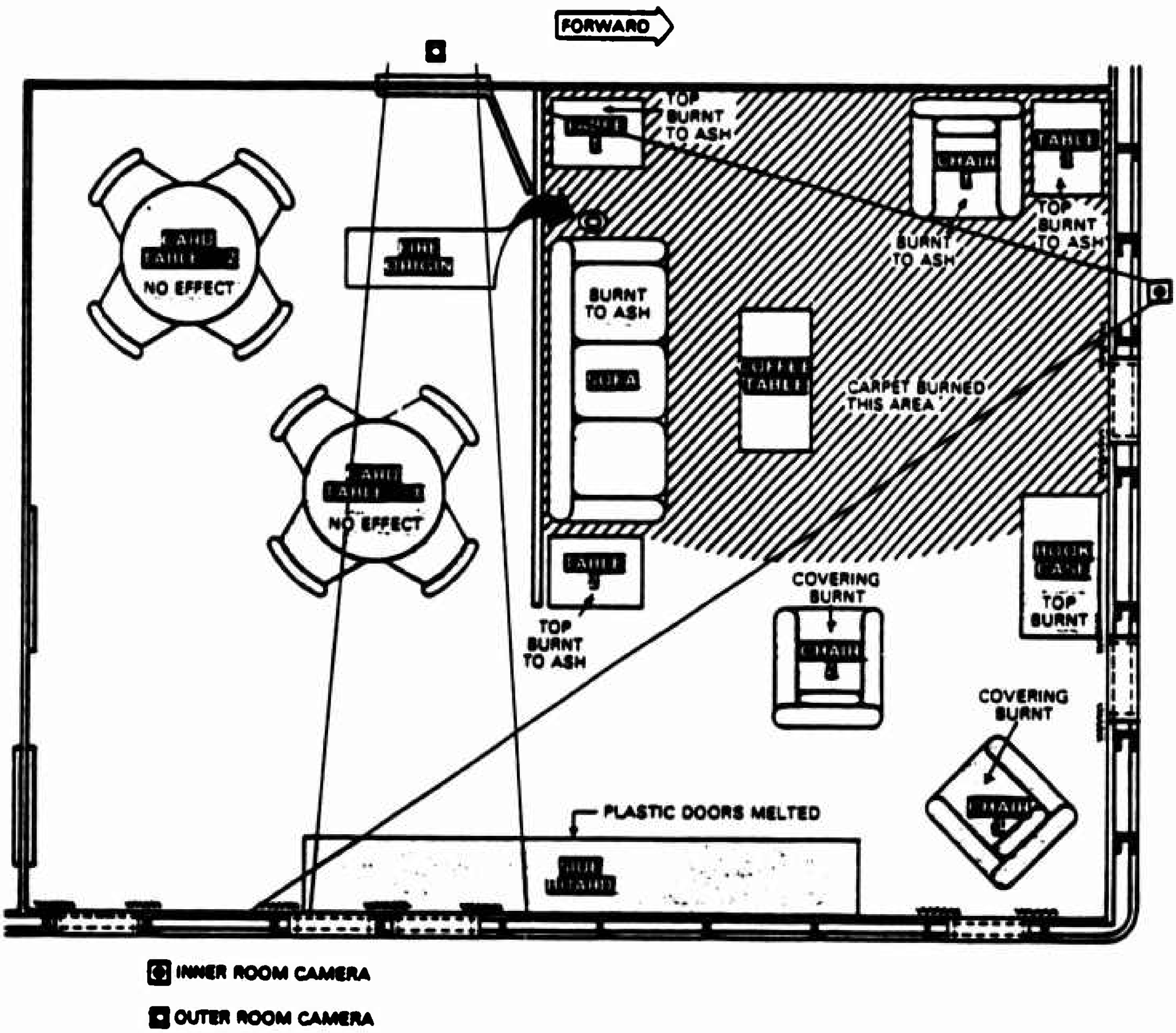


FIGURE 33. Extent of Damage for Burnout 2

TABLE 8

EXTENT OF FIRE DAMAGE FOR BURNOUT 2 (CLOSED VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Lamp shades burnt off - table tops burnt to ash
Table & lamp 2	Lamp shades burnt off - table tops burnt to ash
Table & lamp 3	Lamp shades burnt off - table tops burnt to ash
Chair 1	Totally burnt
Chair 2	Vinyl on back, cushion and left side burnt off - urethane foam burnt some
Chair 3	Vinyl on back, top of arms and cushion burnt
Coffee table	Laminate came off and burnt
Bookcase	Books on top and top shelf burnt
Sideboard	Plastic doors warped but not melted - books and magazines on top burnt
Carpet and pad	Burnt in sofa/chair 1 half of inner room (see below)
Curtains	Material not burnt - thread melted out
Wall covering	Blackened and burnt forward and side bulkheads, all peeled and burnt off partition
Wall base	No effect
Tracking system	Remained intact - no warping
Ceiling material	Cracked panel forward inside corner
Light diffusers	Melted and warped
Combustibles	Plastic bags in waste baskets melted - little burning inside burned out area
Outer Room	
Card tables	No effect
Steel chairs	Slight melting of vinyl
Aluminum chairs	No effect
Bulletin boards	Did not burn
Carpet	Did not burn
Wall covering	Micarta came off (see below) - burnt, sooted above 2'3"
Wall base	No effect
Tracking system	Remained intact - no warping
Ceiling material	Remained intact
Light diffusers	Did not observe
Combustibles	Chips, cards and game board not burnt, checkers melted some, coffee cups melted and burned

4.2 Results of Burnouts with Passive Ventilation (Burnouts 3 and 6)

The ventilation ducts in the overhead of the inner and outer rooms were open to a plenum which in turn was open to the atmosphere for these tests. The burnouts generally progresed in a similar manner even though Burnout 3 began more rapidly (see tables 9 and 10). In both cases, the back of the sofa became involved at approximately the same time that the temperature rise began to accelerate (see figures 34 and 43), which was between 5-1/4 and 5-3/4 minutes. The fire jumped to the shade on lamp 1 at 4 minutes, 51 seconds in Burnout 3 and 6 minutes, 52 seconds in Burnout 6. The involvement of the lamp-shade in each case was instantaneous, as one might have observed in a flashover. The temperature histories were characterized by an early sharp peak and a broad peak in the second half hour of the tests (see figures 34, 35, 43 and 44). Both of the early peaks occurred between 10 and 11 minutes after ignition and exceeded 820 degrees centigrade which is well above the ASTM E119 temperature curve at this time. The second peaks seem to correspond with chair 2 burning which was observed between 23 and 27 minutes for Burnout 3, and 26 and 28 minutes for Burnout 6. The severity of these fires as indicated by the temperature-time product of the upper thermocouples in the inner compartment (area A1) was 565 and 576 degree centigrade - hours respectively for Burnouts 3 and 6 as compared to 762 degree centigrade - hours for the ASTM E119 test fire. The heat flux peaks correspond with the temperature peaks (figures 36 and 45). Unfortunately, the radiometer on the ceiling in the inner room failed during Burnout 3 but the maximum heat flux for Burnout 6 was above 50 kilowatts per square meter.

The weight data presented in figures 37 and 46 is suspect. It indicates that the sofas were totally consumed within the first 10 to 15 minutes of the tests at an average rate for Burnouts 3 and 6 of 6.8 and 3.2 kilograms per minute respectively. The weight increases shown could have been caused by debris falling from the ceiling. Oxygen concentration valleys and carbon monoxide and carbon dioxide peaks (see figures 38 and 47) follow the temperature peaks by a few minutes with the notable exception of a third carbon monoxide peak in each test. These peaks occurred at approximately 40 and 45 minutes from ignition for Burnouts 3 and 6 respectively and were higher than the preceding carbon monoxide peaks. They correspond with vigorous burning in the outer room for each test.

The average temperatures in the doorways (figures 39 and 48) did not follow the temperature histories in the inner rooms. They generally rose and then peaked in the last 20 minutes of each test. These peaks generally corresponded with the burning in the outer room nearer the door. The lower temperatures during the early stages of the test are probably accounted for by hot gases being drawn off through the ventilation ducts before they reached the doorway. Smoke obscuration measured in the doorways reached 100 percent 5 and 7 minutes after ignition in Burnouts 3 and 6 respectively (see figures 40 and 49). This occurred approximately one and a half minutes earlier than the inner compartment was thought to be smoke obscured (tables 9 and 10) as determined by observation of the video tapes. The smoke obscuration data after 7 to 8 minutes is not reliable because the hot gases in the doorway were affecting the phototubes and amplifiers.

The flow of fire gases reported as air velocity (figures 41 and 50) was not as clear-cut as in Burnouts 1 and 2. Flow for Burnout 3 was out of

the lounge in the upper and lower thirds of the doorway and in the vent ducts. The direction of flow shifted several times between in and out of the lounge at the 1.42 meter level. Flow for Burnout 6 was into the lounge in the upper half of the doorway and out in the lower half. The flow probe in the vent duct failed during this test. Oxygen, carbon monoxide and carbon dioxide concentration histories in the doorway (figures 42 and 51) were very similar to those in the inner rooms. The first two carbon monoxide peaks were higher in the doorway than in the inner room.

The extent of damage is displayed in figure 52 and table 11 for Burnout 3 and figure 53 and table 12 for Burnout 6. Both the inner and outer rooms of each lounge burned out. The carpet and pads were reduced to ash throughout the lounges. The perforated aluminum panels melted and dropped from the ceiling. The sofa and chairs 1, 2 and 3 were reduced to ash. Only the steel frames remained of the chairs placed at the card tables. Plastic laminate peeled off all panels in the inner and outer room bulkheads and burned to ash. Several H posts bowed out but retained the joiner panels in both tests as indicated in figures 52 and 53. A few H posts came apart and allowed the panels to fall away from the outer room in Burnout 3. It was determined afterwards that this was due to the lack of a ceiling mounting system outside the room which would have restrained the panels.

TABLE 9

LOG OF OBSERVATIONS FROM BURNOUT 3 (PASSIVE VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition in waste basket - burst of flame
00:17	Flames to top of sofa arm
00:23	Flames 1 foot above arm of sofa
01:00	Vinyl on side of sofa arm burning
01:15	Smoke in upper 1 foot of inner room
02:20	Papers on side table burning - burning plastic dripping on carpet
02:55	Rapid involvement of all papers on side table
03:12	Vinyl on back of sofa burning
03:47	Flames 1 foot above sofa back
04:00	Sustained burning of papers on carpet in front of sofa
04:35	Smoke in upper 2 feet of inner room - fire has progressed horizontally 2 feet across the back of the sofa
04:51	Lampshade 1 burst into flames
05:15	Back of sofa burning and burning plastic dropping on carpet
06:50	Fire completely obscured by smoke
09:55	Audible crackle from fire and flames visible in front of forward camera
10:40	Flames die out - fire glow visible through smoke
19:55	Flames visible through smoke in sofa and table areas
23:10	Flare-up visible through smoke in sofa area
23:25	Flames issuing from chair 2 into inner room
23:55	Extensive flames from chair 2
24:15	Flames near field upper right of camera view and continuing from chair 2
27:30	Flames dying down from chair
28:40	Smoke noticeably clearing from inner room
30:12	Inner room video camera malfunctioned
34:07	Increase in sounds from fire
36:40	Flames visible through smoke from outer room camera
39:30	Visible flames gone from outer room
43:20	Flames occasionally visible
45:00	Flames visible spiraling up from card table top and chair cushion
47:35	Smoke very transparent - furniture outline visible
48:01	Piece of Micarta fell across camera field of view
48:30	Card table top and chair cushions continue to burn
50:20	Chair cushions burnt out
52:00	Smoke denser and table top almost burnt out
53:26	Flames visible issuing from sideboard
58:00	Flames continue to be visible from top of sideboard
62:36	Sprinklers turned on in comparments

TABLE 10

LOG OF OBSERVATIONS FROM BURNOUT 6 (PASSIVE VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition in waste basket
00:40	Flames to the top of sofa arm
00:47	Newspapers on table burning
01:00	Flames to top of sofa back
01:22	Vinyl on side of sofa burning
01:50	Burning plastic dripped onto carpet
02:24	Smoke in upper 1 foot of inner room
03:00	Right front edge of sofa back beginning to burn
03:15	Flames consistently 1 foot above sofa back
05:30	Fire beginning to be obscured by smoke
05:43	Burning plastic dripping from back of burning sofa
06:52	Lamp shade burst into flames
06:58	Fire consuming 2 feet horizontally of sofa back
08:00	Fire consuming 4 feet horizontally of sofa back
08:20	Fire completely obscured by smoke
09:00	Fire barely visible but quite noisy
09:10	Fire not visible
10:20	Burst of flames visible - chair 1 burning
12:20	Flames progressed from right to fill entire foreground of inner room camera
14:30	Transparent flames visible in foreground and background of inner room camera
15:40	Flames being drawn from right side of sofa up to ceiling and over to exhaust duct
19:30	Fire dying and slightly obscured by smoke
24:00	Fire reintensifying
26:50	Chair 2 burning - flames visible from left side
27:45	Smoke obscuration of chair 2
28:05	Flames from left immediately in front of camera
33:40	Inner room almost completely clear of smoke/outer room still smoke obscured/lazy burning from partially consumed materials on deck
39:30	Condition still occurs in inner room/burning of chair 3 barely visible through smoke from outer room camera
41:30	Burning of chair 3 still visible
43:45	Flames burst forth in front of outer room camera
44:25	Flames in outer room visible from inner room camera
44:40	Smoke building up in inner room
45:30	Inner room smoke obscured/outer room actively burning
49:10	Carpet in outer room actively burning
49:40	Aluminum chair collapsed
51:20	Smoke clearing inner room/burning in outer room
57:00	Conditions continue - materials on sideboard burning
60:10	Sprinklers on

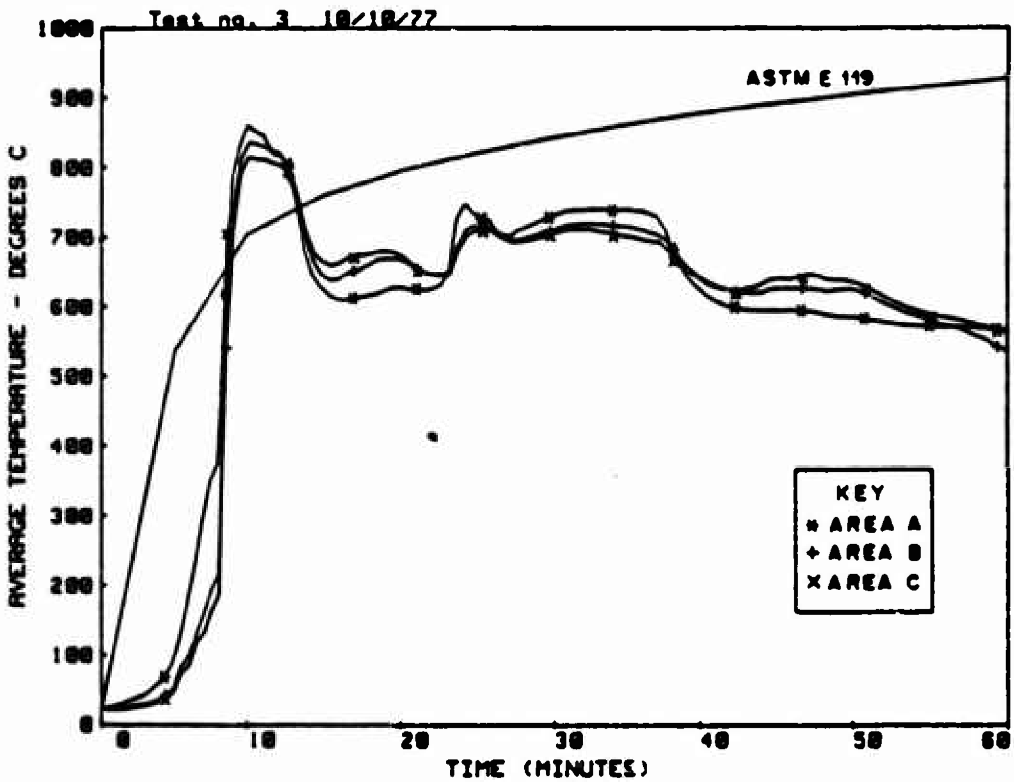


FIGURE 34. Average Upper (Level 1) Gas Temperature Histories for Burnout 3

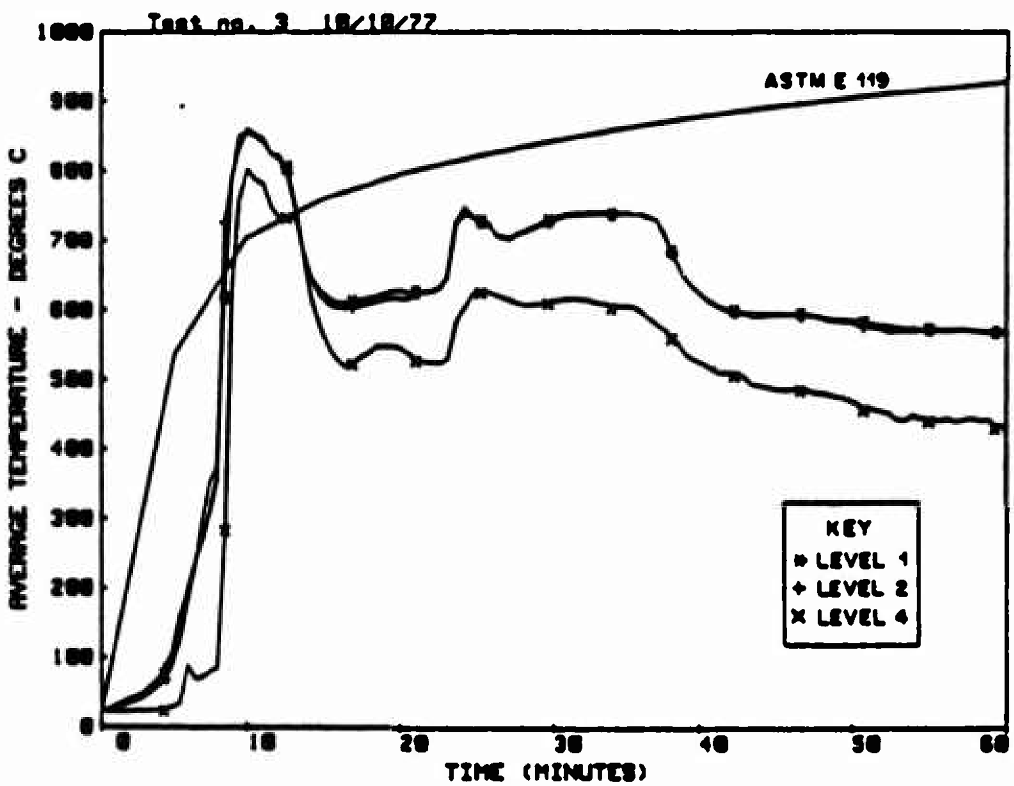


FIGURE 35. Average Inner Room (Area A) Gas Temperature Histories for Burnout 3

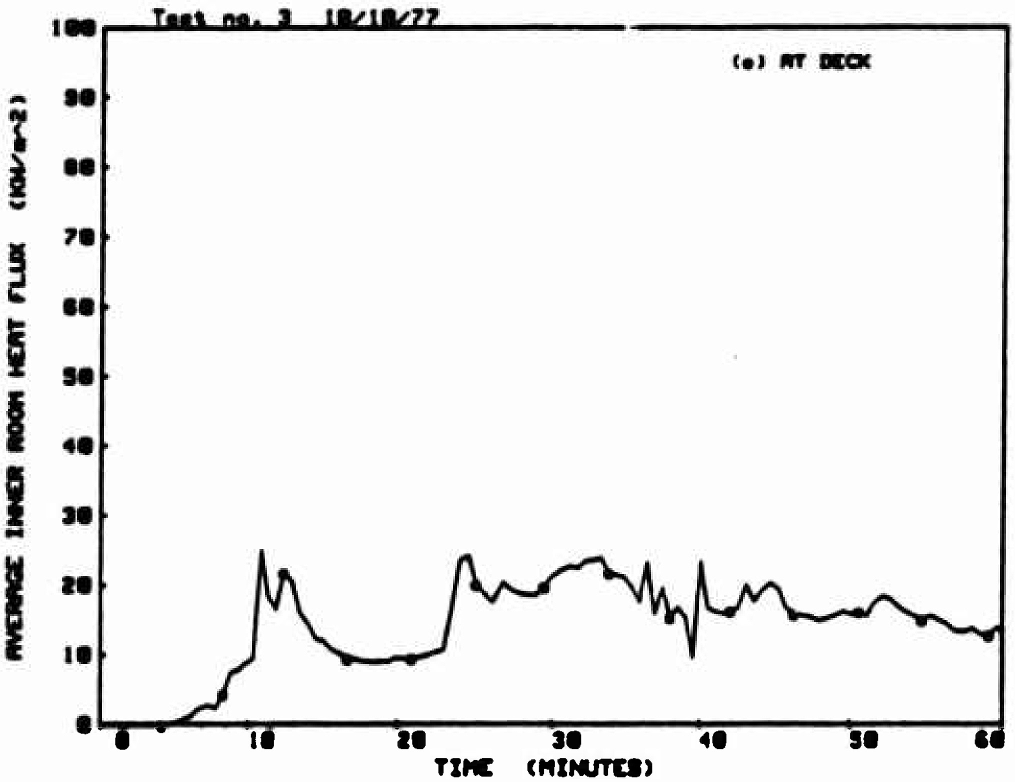


FIGURE 36. Average Inner Room Heat Flux Histories for Burnout 3

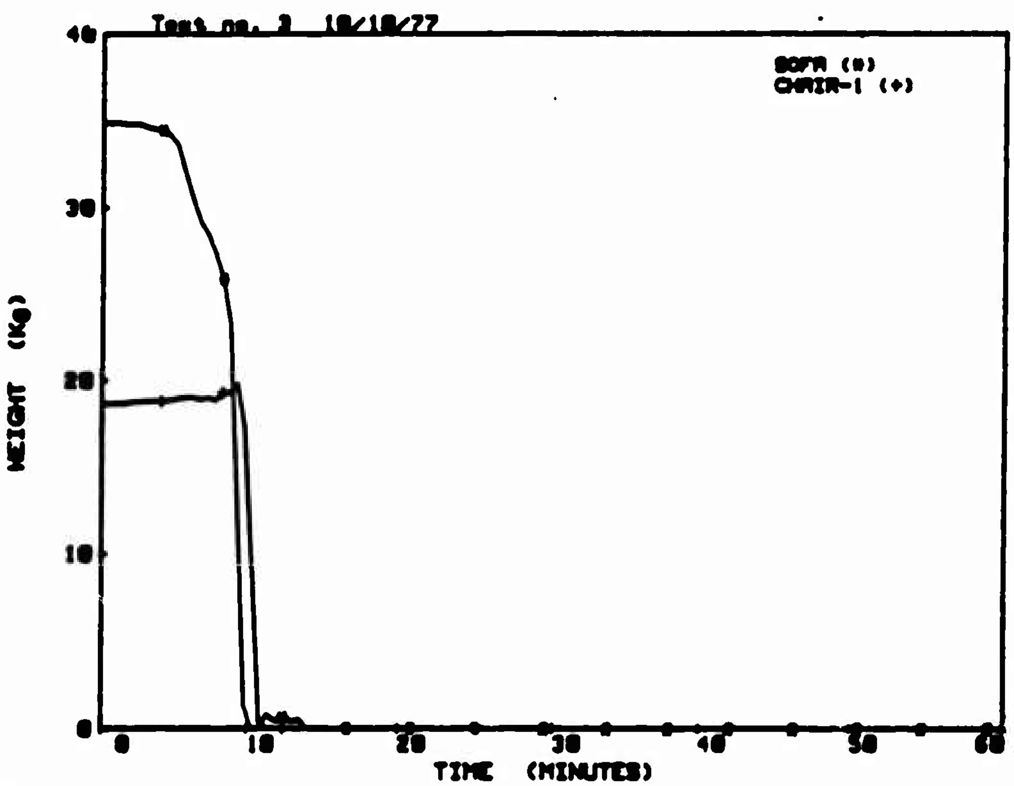


FIGURE 37. Weight Loss of Sofa and Chair 1 for Burnout 3

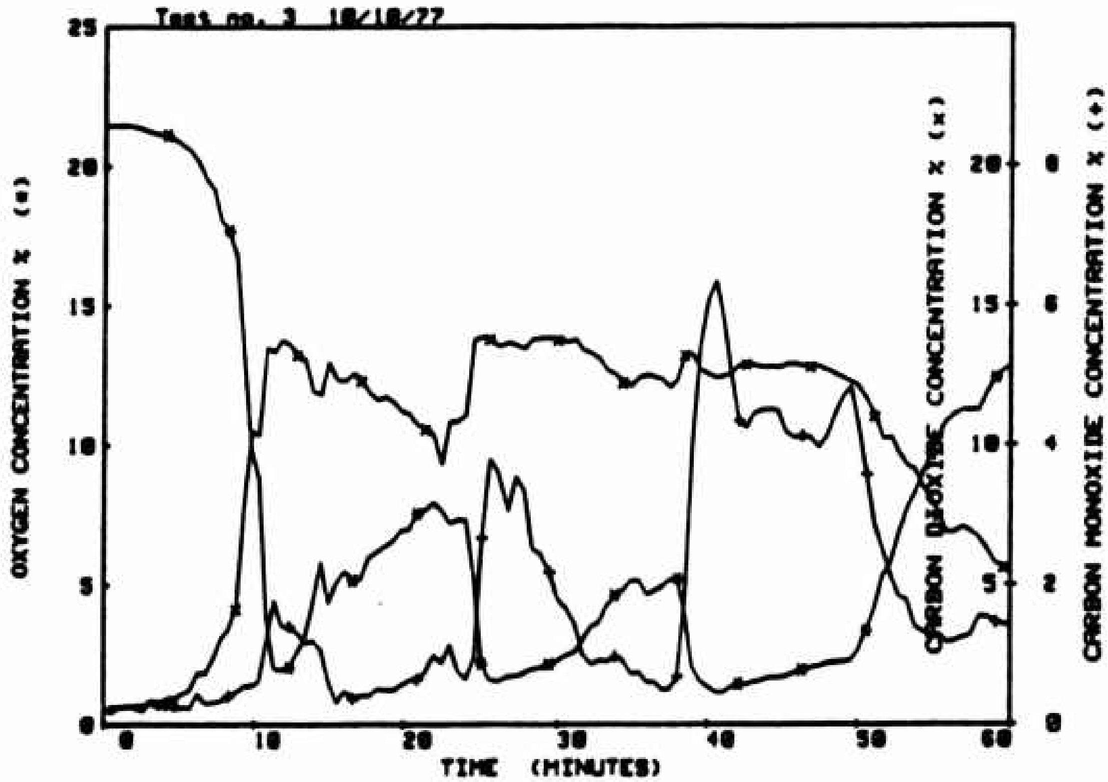


FIGURE 38. Inner Room Gas Concentration Histories for Burnout 3

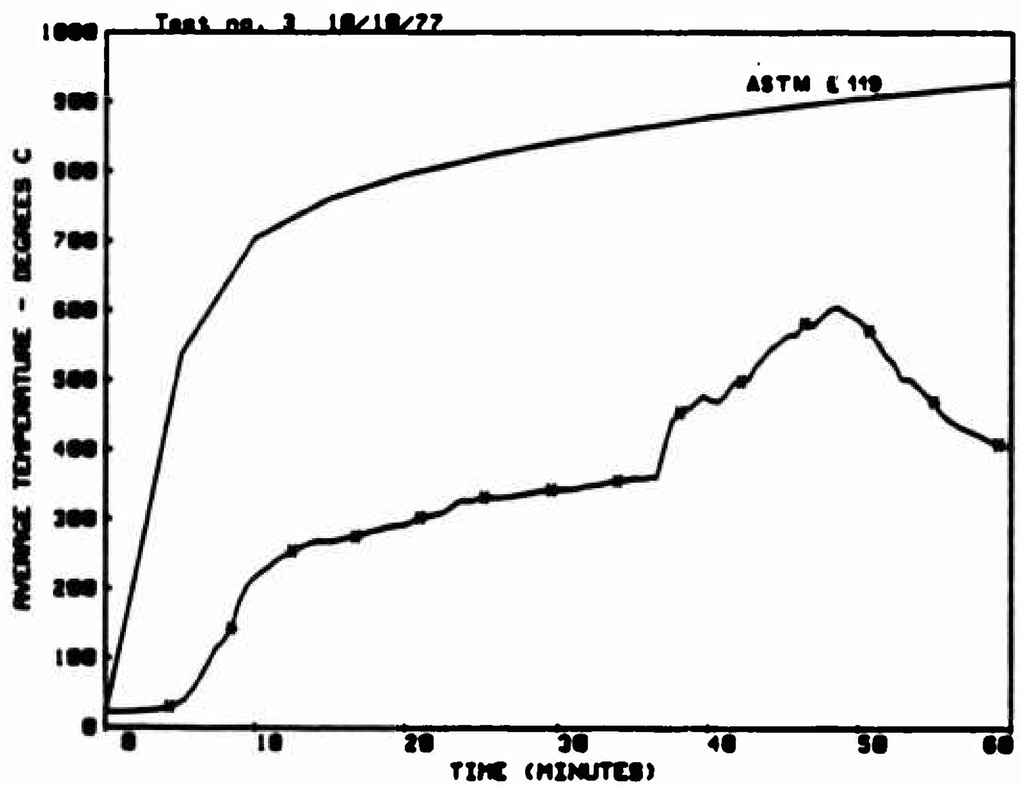


FIGURE 39. Average Doorway Temperature History for Burnout 3

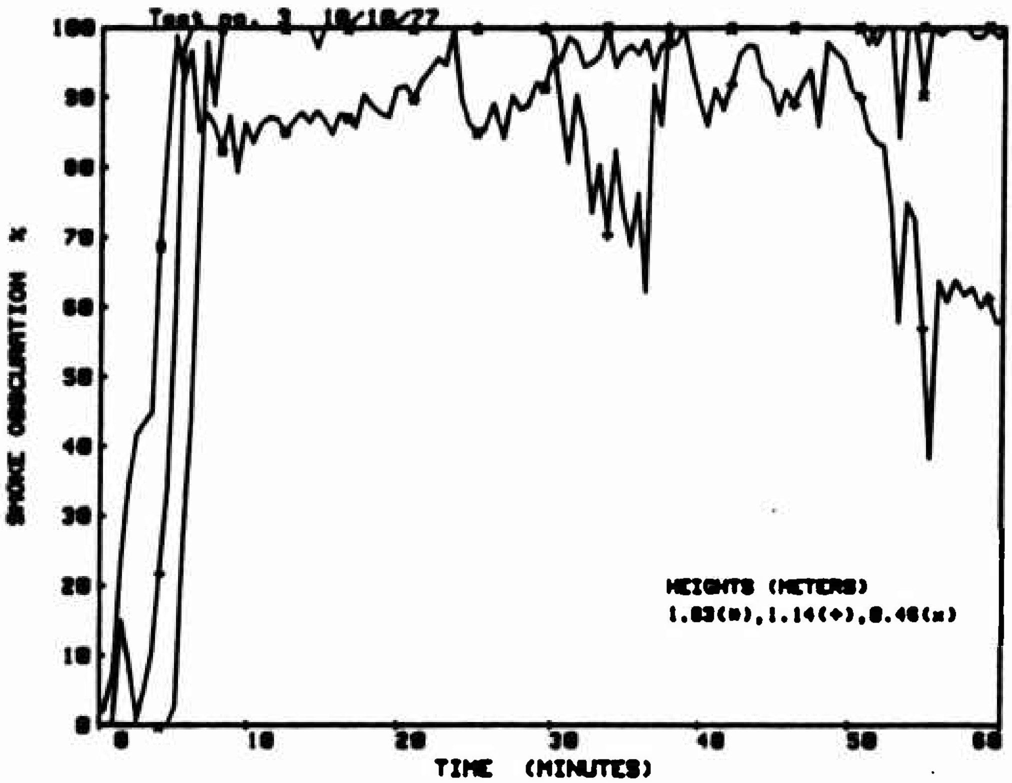


FIGURE 40. Smoke Obscuration Histories in Doorway for Burnout 3

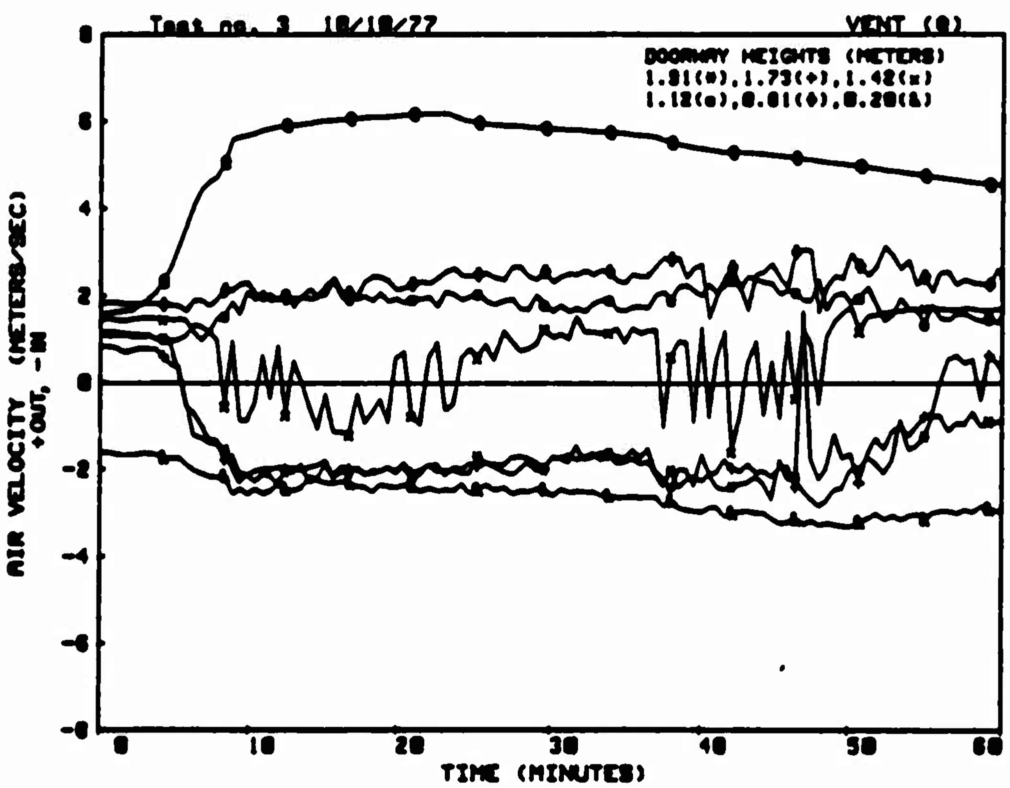


FIGURE 41. Air Velocity Histories Through Doorway & Vent for Burnout 3

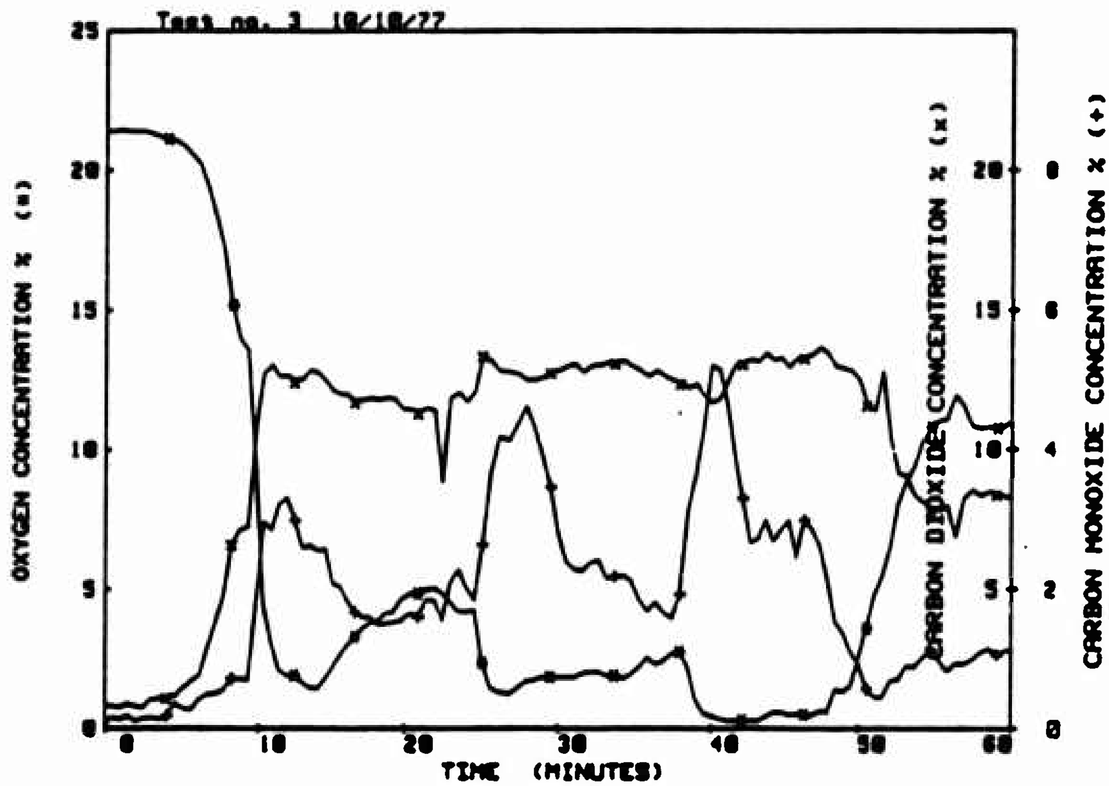


FIGURE 42. Doorway Gas Concentration Histories for Burnout 3

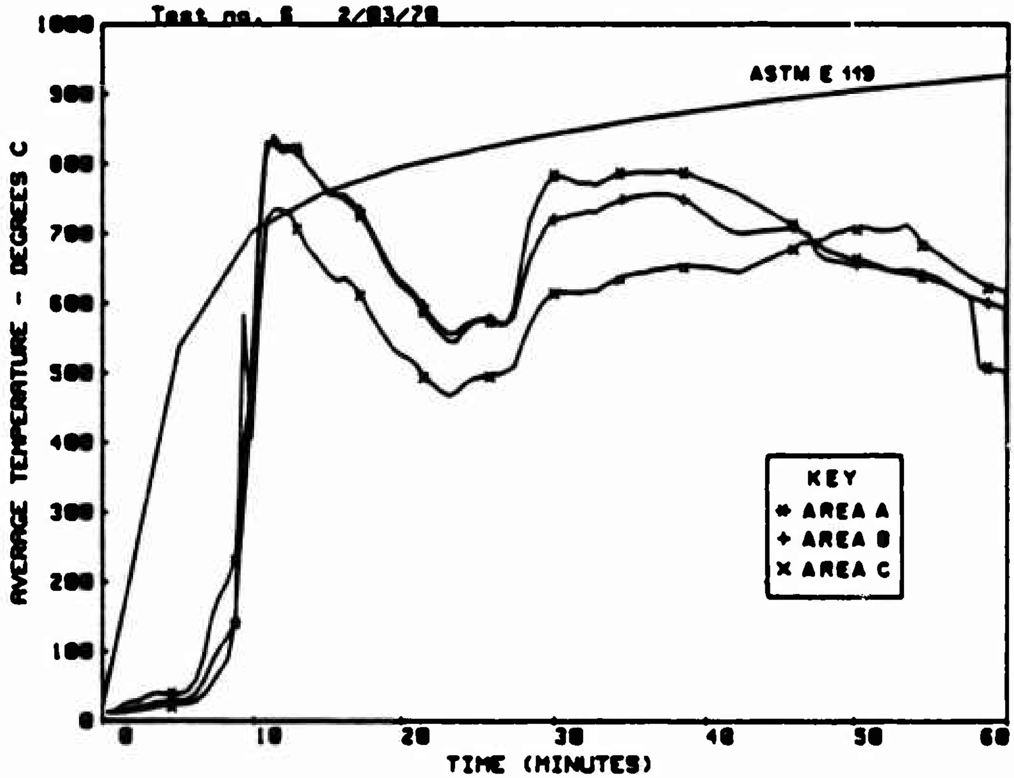


FIGURE 43. Average Upper (Level 1) Gas Temperature Histories for Burnout 6

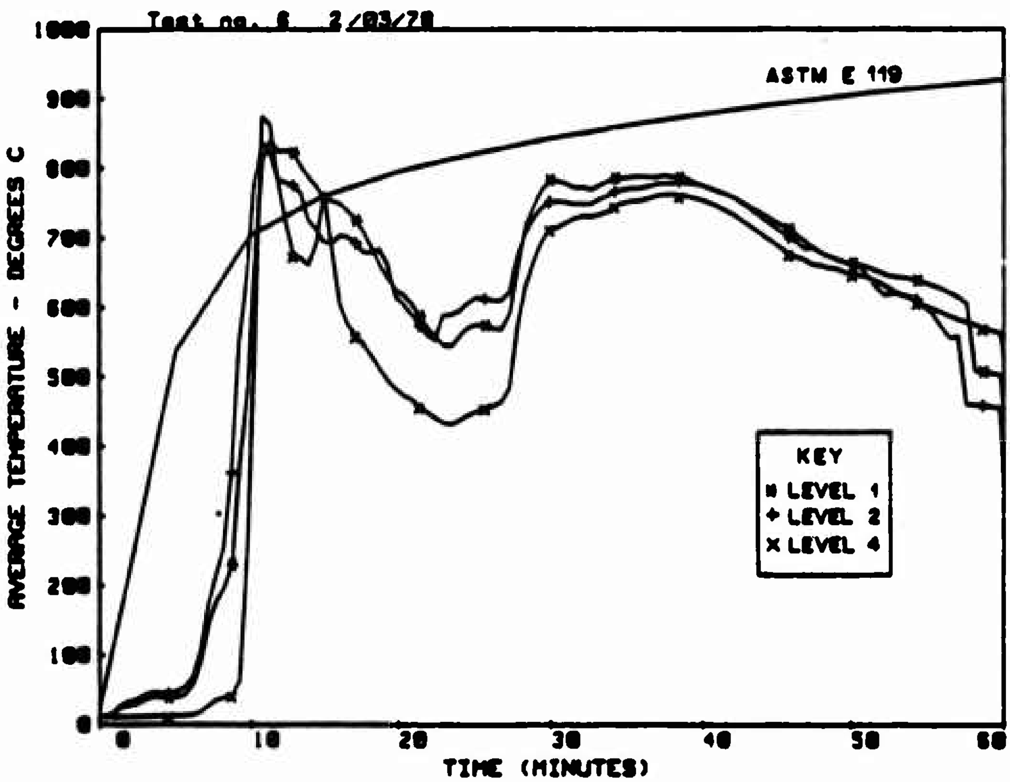


FIGURE 44. Average Inner Room (Area A) Gas Temperature Histories for Burnout 6

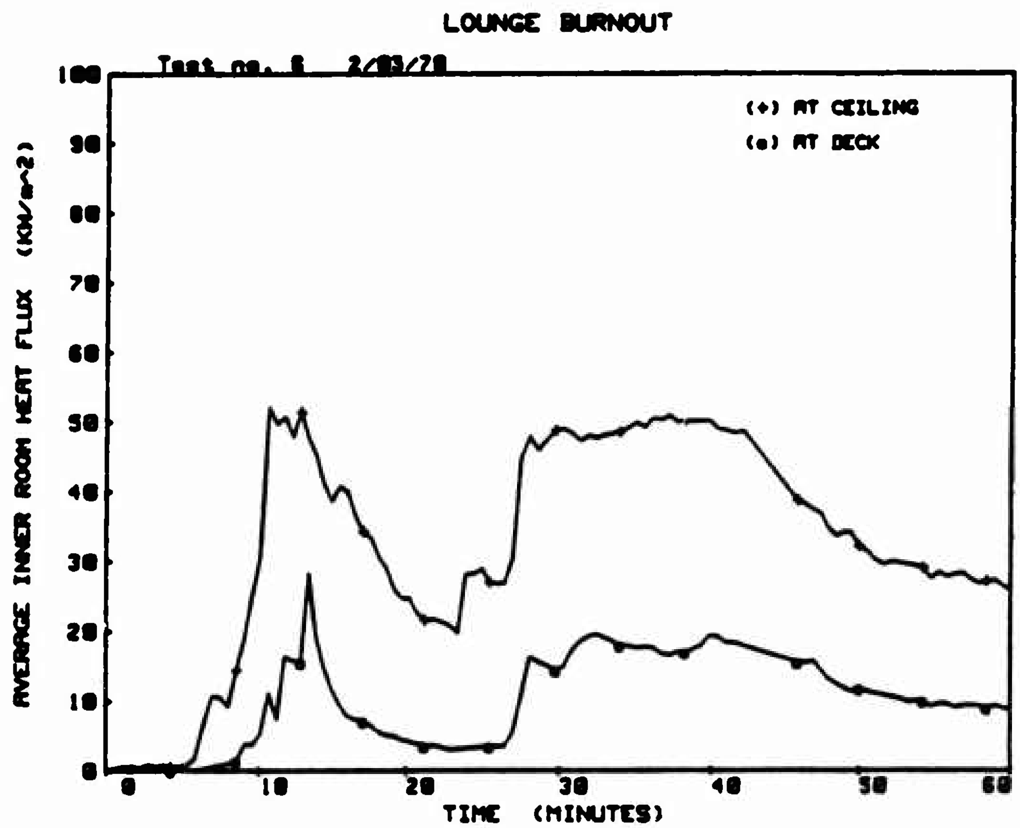


FIGURE 45. Average Inner Room Heat Flux Histories for Burnout 6

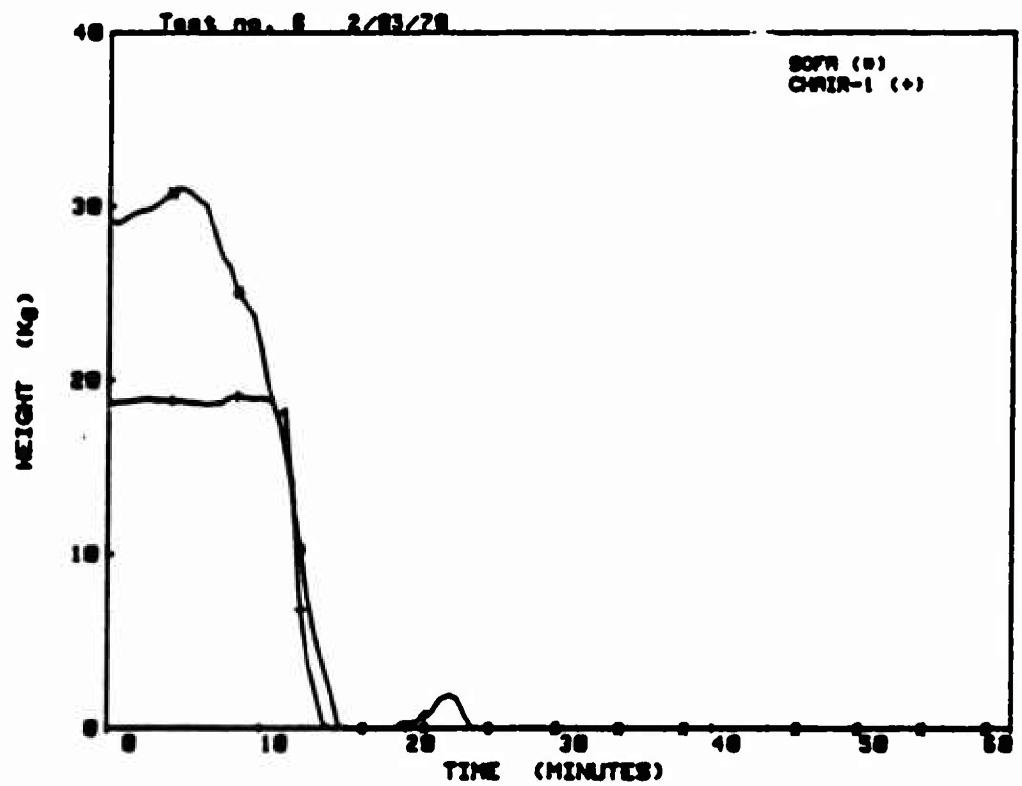


FIGURE 46. Weight Loss of Sofa and Chair 1 for Burnout 6

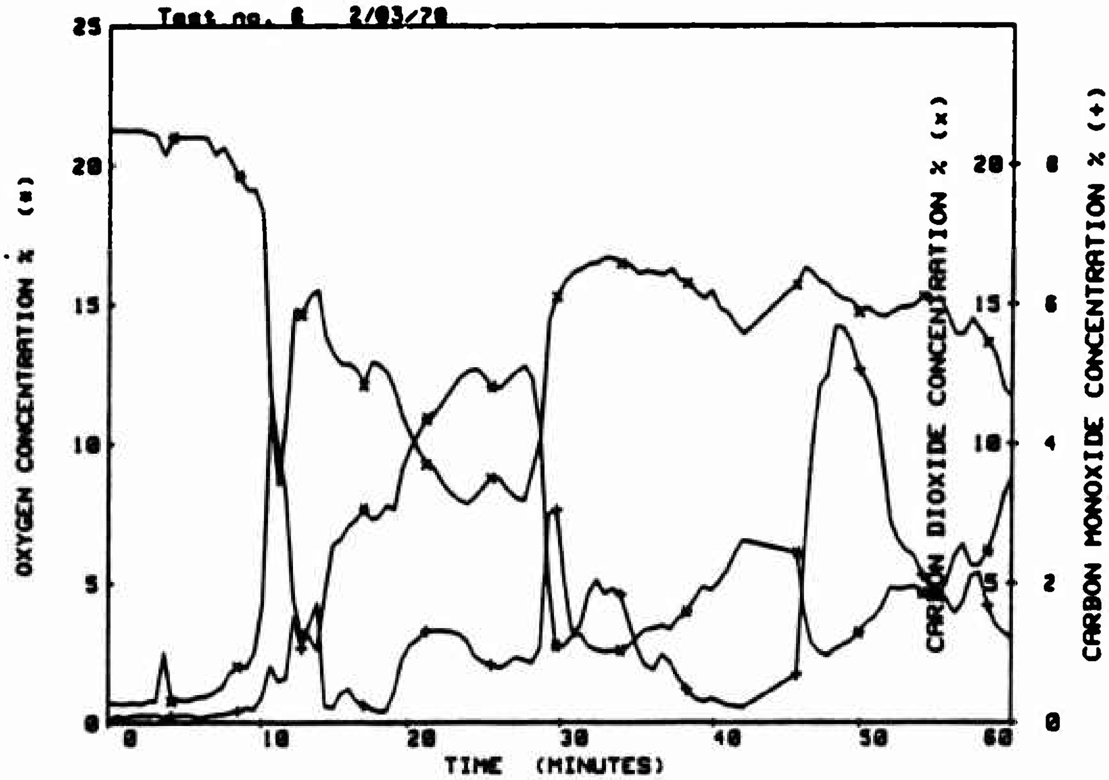


FIGURE 47. Inner Room Gas Concentration Histories for Burnout 6

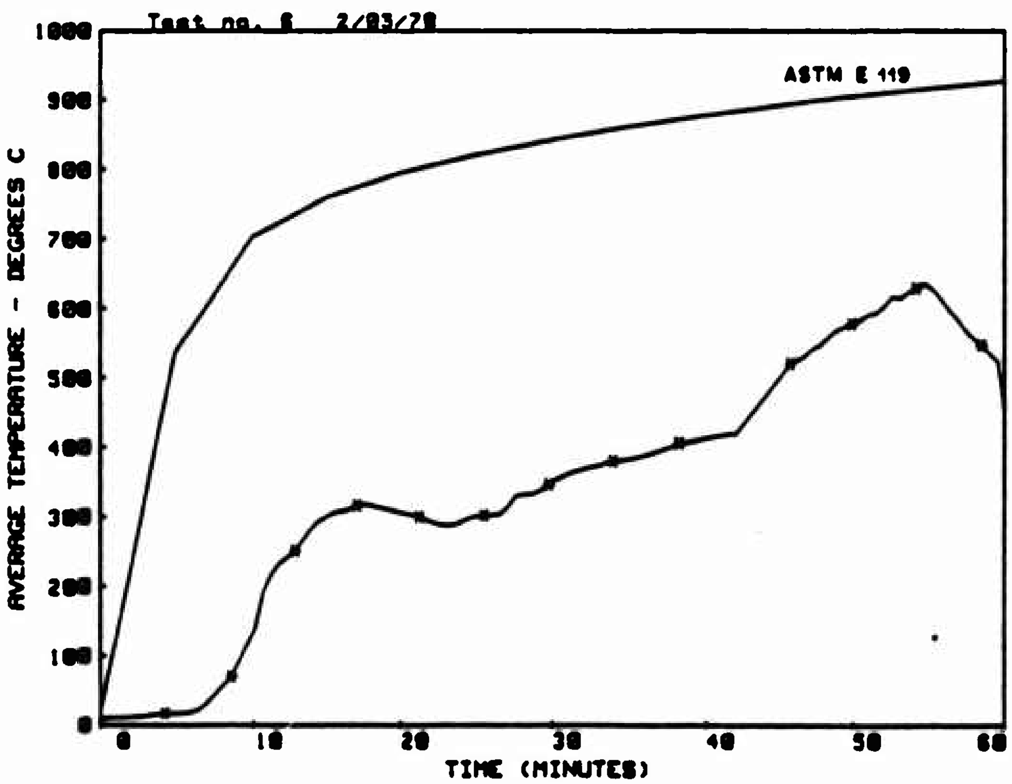


FIGURE 48. Average Doorway Temperature History for Burnout 6

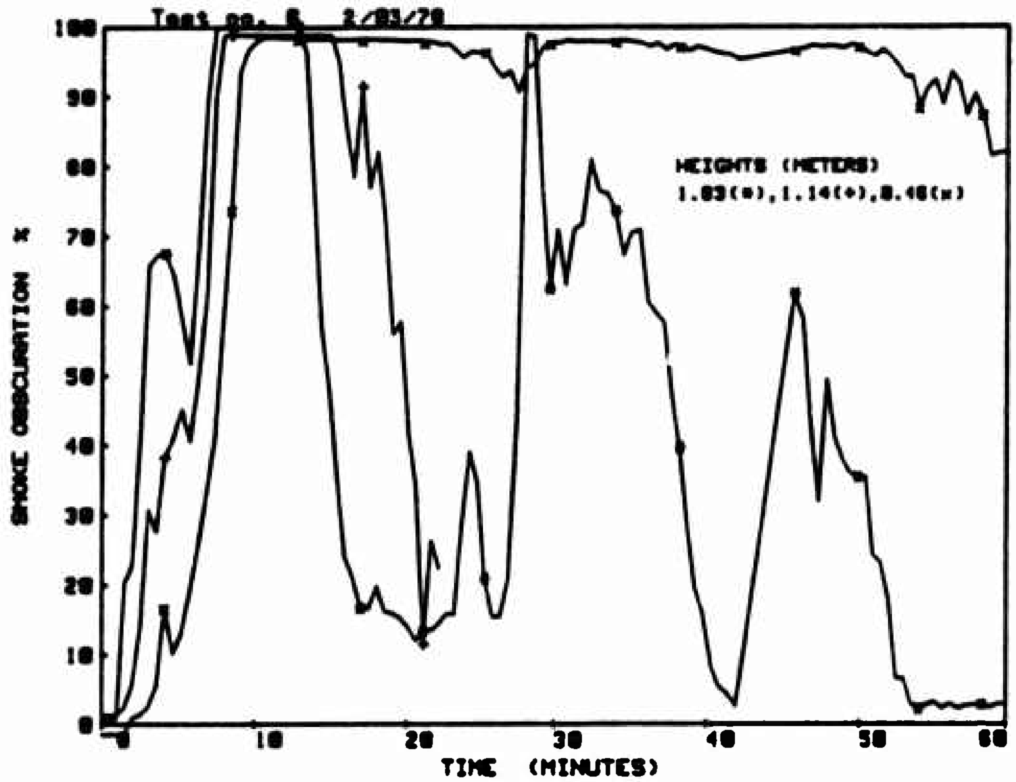


FIGURE 49. Smoke Obscuration Histories in Doorway for Burnout 6

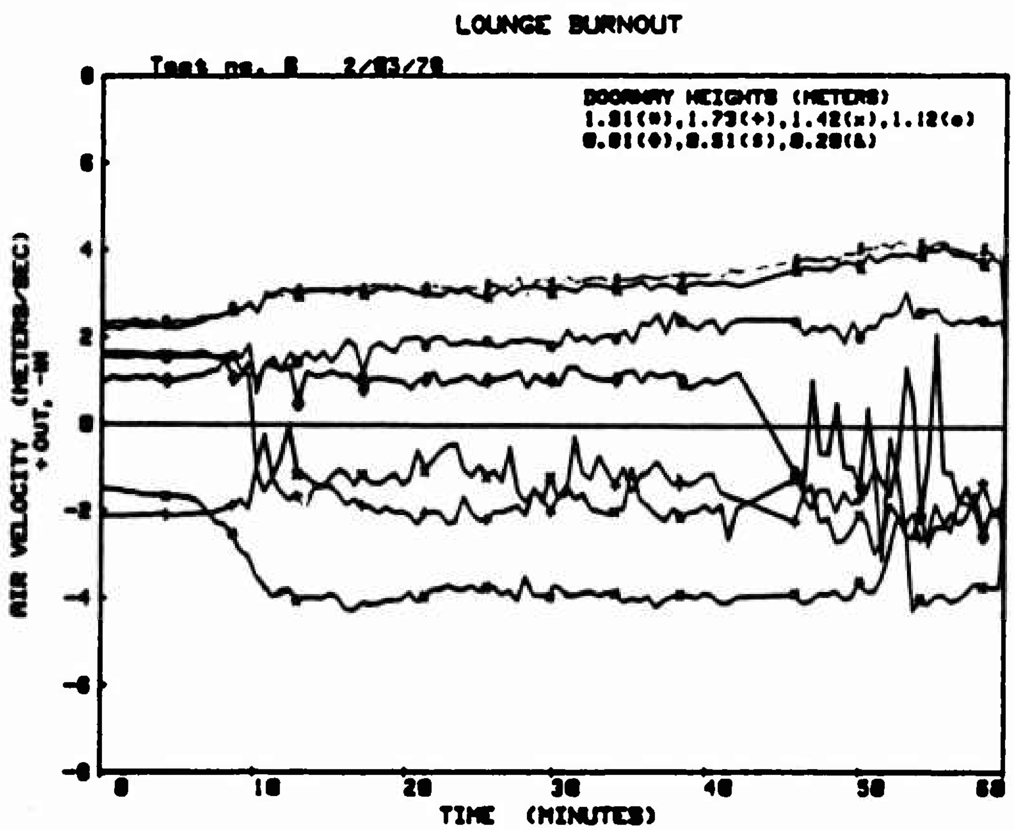


FIGURE 50. Air Velocity Histories Through Doorway for Burnout 6

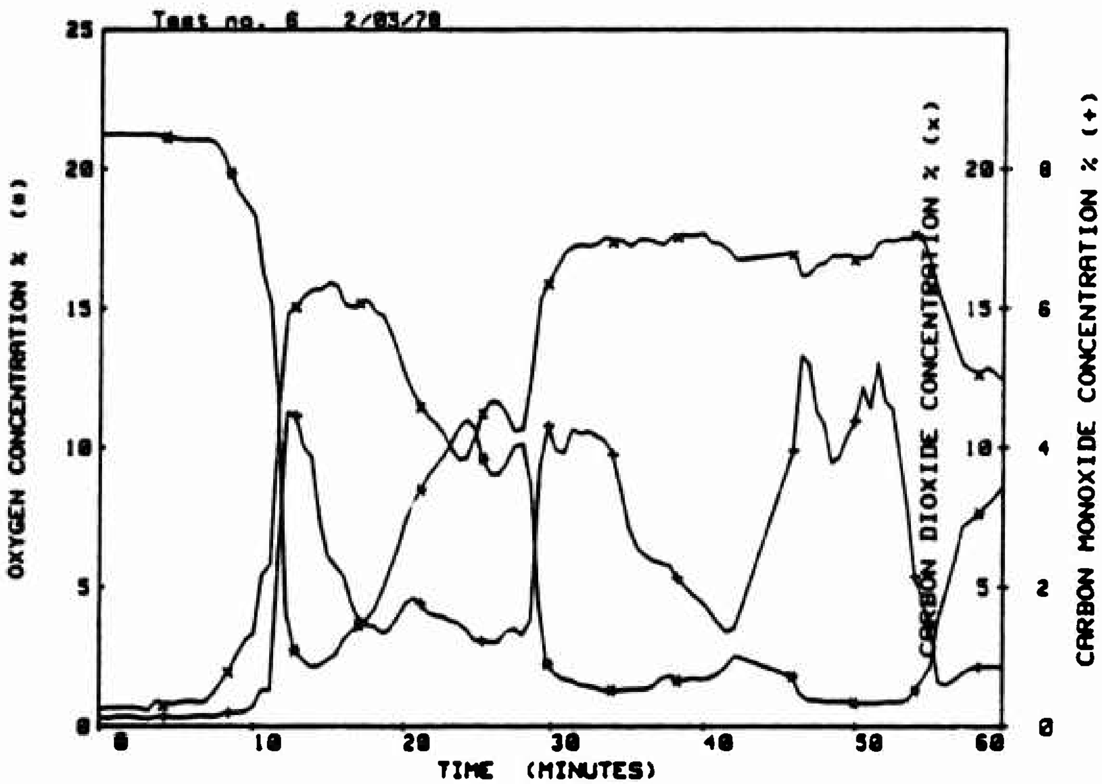


FIGURE 51. Doorway Gas Concentration Histories for Burnout 6

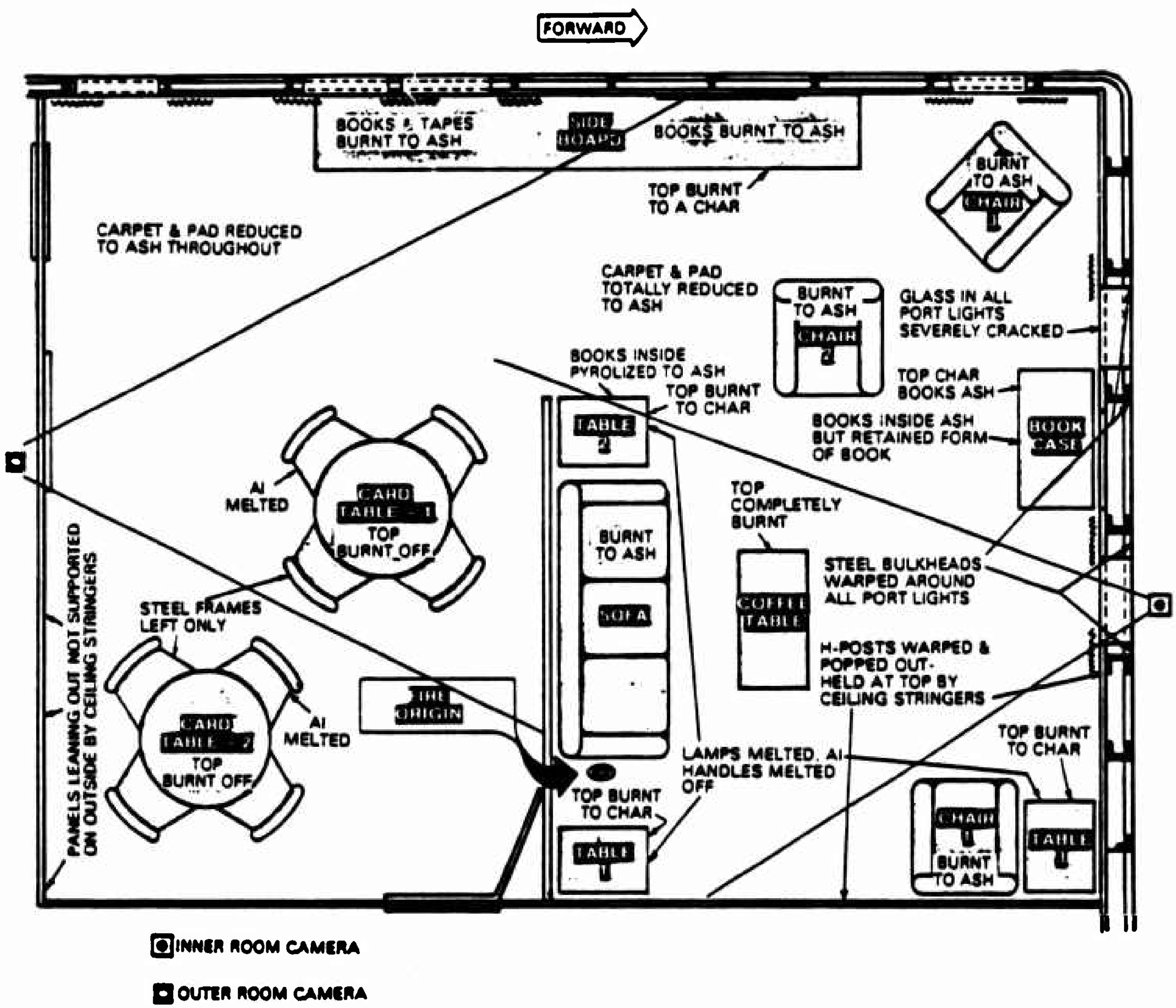


FIGURE 52. Extent of Damage for Burnout 3

TABLE 11

EXTENT OF FIRE DAMAGE FOR BURNOUT 3 (PASSIVE VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Shades and table top burnt to ash/char; lamp melted
Table & lamp 2	Shades and table top burnt to ash/char; lamp melted
Table & lamp 3	Shades and table top burnt to ash/char; lamp melted
Chair 1	Totally burnt to ash
Chair 2	Totally burnt to ash
Chair 3	Totally burnt to ash
Coffee table	Top totally burnt to ash
Book case	Top, books on top and inside burnt to thick char
Sideboard	Top burnt to thick char - books, etc., burnt out
Carpet and pad	Totally burnt to ash
Curtains	Material not burnt - thread melted out
Wall covering	Came off in sheets and burned
Wall base	No effect
Tracking system	H posts warped and disengaged - held at top by ceiling
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Completely burnt
Outer Room	
Card tables	Tops burnt to char - fell off
Steel chairs	All cushions burned - only steel frame left
Aluminum chairs	All cushions burned - aluminum melted
Bulletin boards	Burned and fell to deck
Carpet and pad	Totally burnt to ash
Wall covering	Came off in sheets and burnt
Wall base	No effect
Tracking system	H post warped and disengaged - panels fell away
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Completely burnt

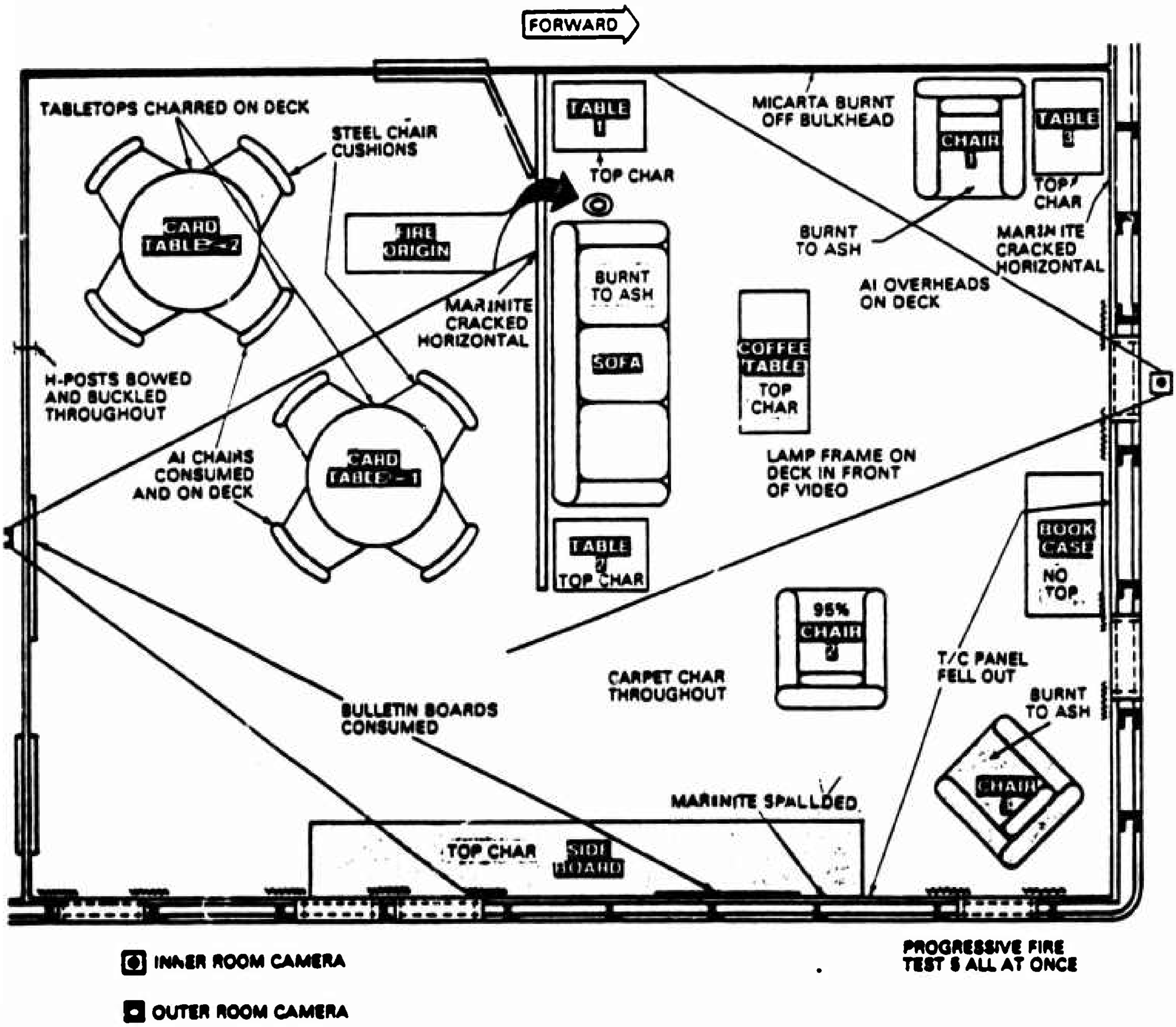


FIGURE 53. Extent of Damage for Burnout 6

TABLE 12

EXTENT OF FIRE DAMAGE FOR BURNOUT 6 (PASSIVE VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Shades and table top burnt to ash/char; lamp melted
Table & lamp 2	Shades and table top burnt to ash/char; lamp melted
Table & lamp 3	Shades and table top burnt to ash/char; lamp melted
Chair 1	Totally burnt to ash
Chair 2	Totally burnt to ash
Chair 3	Totally burnt to ash
Coffee table	Top totally burnt to ash
Book case	Top, books on top and inside burnt to thick char
Sideboard	Top burnt to thick char - books, etc., burnt out
Carpet and pad	Totally burnt to ash
Curtains	Material not burnt - thread melted out
Wall covering	Came off in sheets and burned
Wall base	Small cracks-inner surface only
Tracking system	Minor warping
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Completely consumed
Outer Room	
Card tables	Tops burnt to char - fell off
Steel chairs	All cushions burned - only steel frame left
Aluminum chairs	All cushions burned - aluminum melted
Bulletin boards	Burned and fell to deck
Carpet and pad	Totally burnt to ash
Wall covering	Came off in sheets and burnt
Wall base	No effect
Tracking system	H post warped
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Completely consumed

4.3 Results of Burnouts with Forced Ventilation (Burnouts 4 and 5)

Air was forced in the ventilation ducts in the inner and outer rooms at the rate of 360 cubic feet per minute for these tests. The burnout generally progressed in a similar manner with the events in Burnout 5 occurring approximately 2 minutes earlier than the events in Burnout 4 (see tables 13 and 14). The back of the sofa became involved at approximately 4 minutes in Burnout 5 and it became involved at 6 minutes in Burnout 6. This involvement led the accelerated temperature rise (see figures 54 and 62) by approximately 1 minute for each test. The fire jumped to the shade on lamp 1 at approximately 5-1/2 minutes from ignition in each case with a suddenness resembling a flashover. The temperature histories were characterized by an early sharp peak and a broad peak in the second half hour of the test (see figures 54, 55, 62 and 63). The valley between peaks was quite pronounced for Burnout 4 and the second peak exceeded 700° C which was higher than the second peak in Burnout 5. The severity of these fires, as indicated by the temperature-time product of the upper thermocouples in the inner compartment (area A-1), was 448 and 584°C - hours respectively for Burnouts 4 and 5 as compared to 762°C - hours for ASTM E119 test fire. Thus, Burnout 5 was more severe than Burnout 4. The heat flux peaks generally corresponded with the temperature peaks as shown in figures 56 and 64. The radiometer on the ceiling in the inner room failed at approximately 7 minutes into Burnout 4 but the maximum heat flux for Burnout 5 was above 75 kilowatts per square centimeter.

The weight data presented in figures 57 and 65 is suspect. It indicated that the sofas and chairs were totally consumed in very short time periods. Its value is as an indicator of when the respective pieces of furniture began to be consumed by the fire. All items except chair 2 in Burnout 4 were consumed in the first 10 to 12 minutes which corresponds with the initial temperature peaks. Chair 2's consumption occurred at approximately 27 minutes which could explain the sharper secondary temperature peak in Burnout 4 whereas the consumption of chairs 1 and 2 in Burnout 5 between 11 and 14 minutes after ignition may have been the cause of the elimination of the deep temperature valley. Oxygen concentration valleys and carbon monoxide and carbon dioxide peaks (see figure 58 and 66) followed the temperature peaks by a few minutes with the notable exception of the first 16 minutes in Burnout 5. During this time, the gas tube which transported the gas from the fire to the analyzers had become disconnected and was repaired at 16 minutes and 37 seconds. From this point on, the gas concentration for Burnout 5 corresponded with the temperature profiles.

The average temperature in the doorway (figure 59) for Burnout 4 generally followed the form of the temperature history in the inner room. The average temperature in the doorway for Burnout 5 (figure 67) however, peaked in the 20-25 minute range which corresponded to a valley in the inner room temporature at this time. This peak generally corresponded with the vigorous burning of the chairs, cushions and table top in the outer room. Smoke obscuration measured in the doorways reached 100% at approximately 5 minutes after ignition of both Burnouts 4 and 5 (see figures 60 and 68). This was approximately 1-2 minutes earlier than the inner room was thought to be smoke obscured (tables 13 and 14) as determined by observation of the video tapes. Again, the smoke obscuration data after 7-8 minutes is not reliable because the hot gases in the doorway were affecting the photo tubes and amplifiers.

The flow of fire gases is not reported for these two tests because the majority of the bi-directional air flow probes gave erratic data. Oxygen, carbon dioxide and carbon monoxide concentration histories in the doorways (figures 61 and 69) were of the same general shape as those in the inner room. The broad carbon monoxide plateau in the latter half of Burnout 4 corresponds with the average temperature histories at this time.

The extent of damage is displayed in figure 70 and table 15 for Burnout 4 and figure 71 and table 16 for Burnout 5. Both the inner and outer rooms of each lounge burned out. The carpets and pads were reduced to ash throughout the lounges. The perforated aluminum panels melted and dropped from the ceiling except near the ventilation terminals. In these areas, some aluminum panel and the aluminum ventilation louvers remained intact. Only the steel frames remained of the chairs placed at the card tables. Plastic laminate peeled off all panels in the inner and outer rooms and burned to ashes. Several H posts warped and became disengaged but the panels remained in place. Fire came over the top of the after bulkhead in Burnout 4 and scorched the upper 2 feet of the outside of the panels. This was due to a poor installation of the panels in the joiner system and not a deficiency in the materials.

TABLE 13

LOG OF OBSERVATIONS FROM BURNOUT 4 (FORCED VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition in waste basket
01:40	Flames above waste basket
02:16	Flames above arm of sofa
02:38	Arm of sofa burning
02:45	Flames 1 foot above sofa back
02:50	Burning plastic dripping onto carpet
02:55	Smoke in upper 1 foot of inner room
03:15	Top of sofa arm burning
04:20	Right side of sofa back burning
05:00	Newspaper on table 1 burst into flames
05:35	Fire progressed horizontally 2 feet across front of sofa back
05:48	Lampshade on table 1 burst into flames
06:00	Back of sofa back burning
06:40	Top of sofa cushions burning Smoke beginning to obscure flames Carpet burning below sofa
07:09	Chair 1 burst into flames
07:35	Flames totally smoke obscured - fire noisy
09:10	Flames in left foreground
09:40	Flames in entire foreground
11:50	Flames totally smoke obscured
24:00	Inner and outer rooms continue to be smoke obscured
30:25	Lazy flames breaking through smoke in foreground of inner room camera
31:50	Flames dying out
32:30	Flames in lower right foreground
34:40	Flames dying out
43:00	Fire visible through smoke in outer room
47:00	Fire continues to be visible in outer room
50:20	Smoke clearing in outer room
51:00	Chair barely visible through smoke - burning throughout
52:00	Flames building
58:40	Flames from books on top of sideboard
63:28	Sprinklers turned on

TABLE 14

LOG OF OBSERVATIONS FROM BURNOUT 5 (FORCED VENTILATION)

TEST TIME	OBSERVATION
00:00	Ignition
00:14	Flames to top of sofa arm
00:50	Flames to top of sofa back
00:54	Newspaper on table 1 caught fire
01:00	Plastic burning on side of sofa
01:20	Smoke in upper 1 foot of room
01:35	Burning plastic dripping onto carpet
01:43	Front and top of sofa back burning
02:08	Flames 1 foot above sofa back
02:50	Smoke beginning to obscure compartment
03:40	Outer compartment obscured
04:10	Burning plastic dropping from back of sofa
04:50	Fire 2 feet across back of sofa
05:15	Fire completely across back of sofa back
05:20	Fire 2 feet across front of sofa back
05:28	Lamp shade burst into flames
05:43	Newspaper in front of table 1 burst into flames
05:48	Newspaper next to chair 1 burst into flames
05:52	Sofa side of chair 1 burst into flames
06:05	Fire totally obscured by smoke
06:40	Smoke obscured flames from chair 1
08:15	Flames in front of inner room camera
09:30	Entire field of view inner room camera in flames Right arm of chair 1 burning
12:00	Fire smoke obscured
14:30	Flame building up in front of inner room camera
15:25	Carpet burst into flames in front of outer room camera
17:00	Fire visible on inner and outer room carpets
17:20	Fire totally smoke obscured
18:25	Fire visible in outer room
18:55	Collapsed aluminum chair visible/chair cushions burning/inner room filled with smoke
21:45	Chair cushions and table top continue to burn
26:00	Chair cushions burned out
33:10	Inner room burning in vicinity of table 1 - smoke clearing
34:20	Top of sideboard, chair 3 and table 2 burning
36:00	Card table top burned out
36:20	Remains of sofa flaring up
44:00	Top of sideboard, chair 3, tables 1 and 2 and sofa remains still burning/chair 3 collapsed
50:00	Tops of tables 1 and 2, and sideboard and remains of sofa and chair 3 still burning.
55:00	Above items still burning but less actively
58:40	Table 1 burned out
60:10	Sprinklers turned on

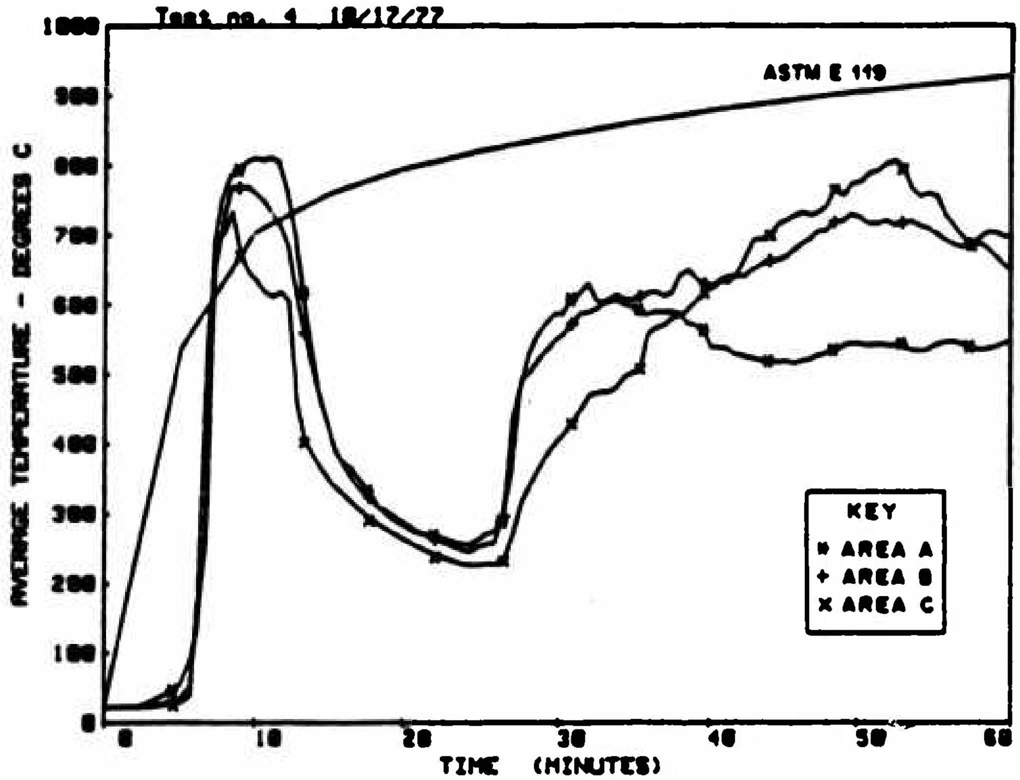


FIGURE 54. Average Upper (Level 1) Gas Temperature Histories for Burnout 4

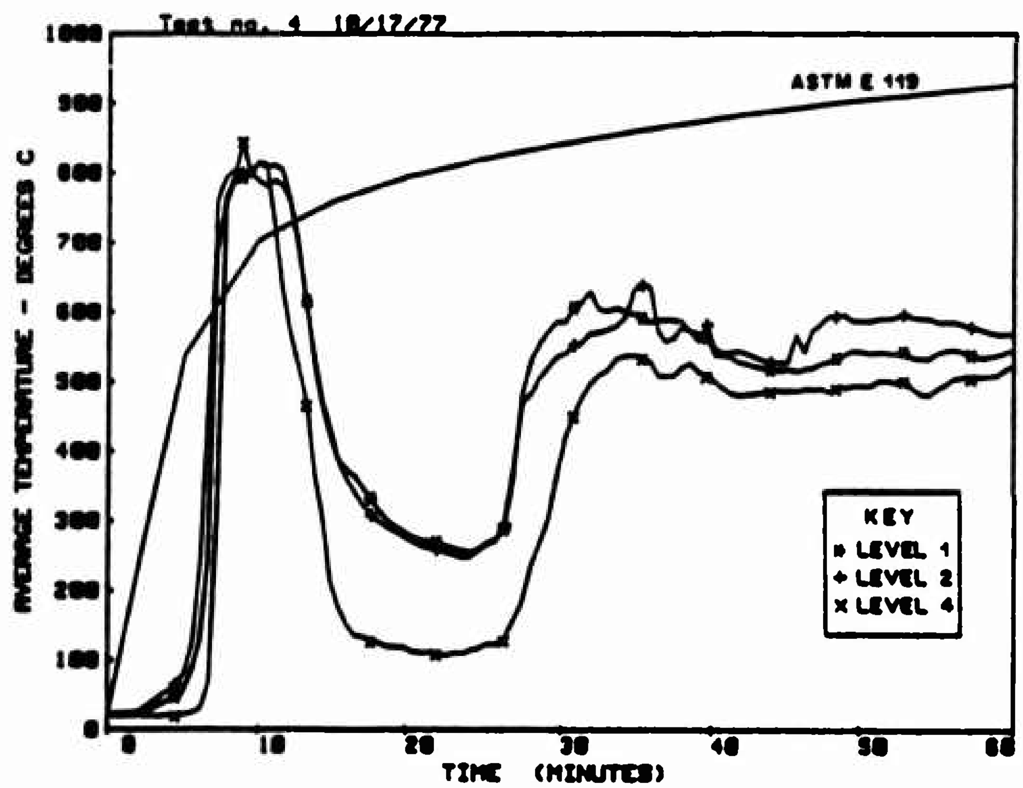


FIGURE 55. Average Inner Room (Area A) Gas Temperature Histories for Burnout 4

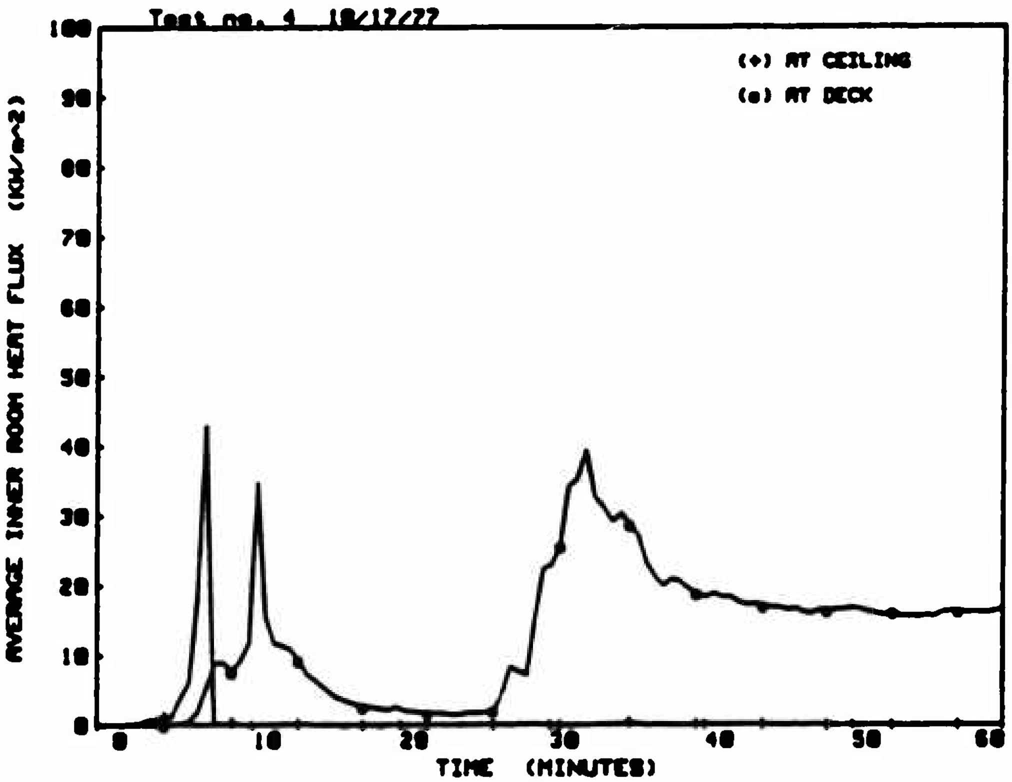


FIGURE 56. Average Inner Room Heat Flux Histories for Burnout 4

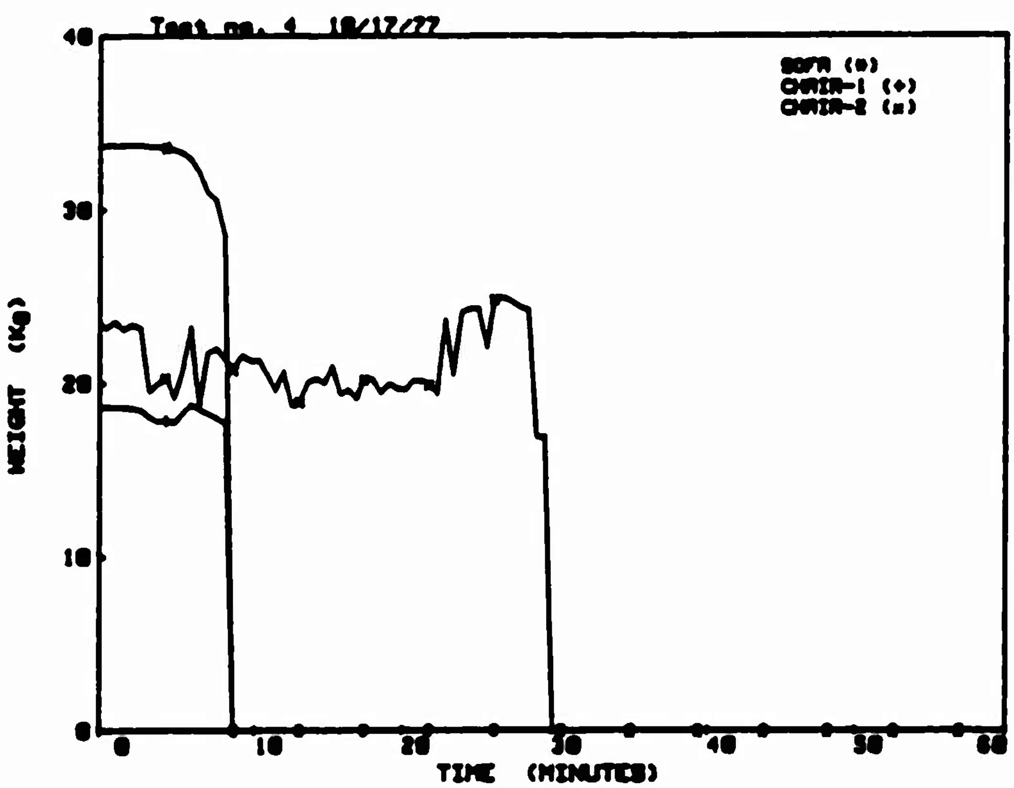


FIGURE 57. Weight Loss of Sofa and Chairs 1 and 2 for Burnout 4

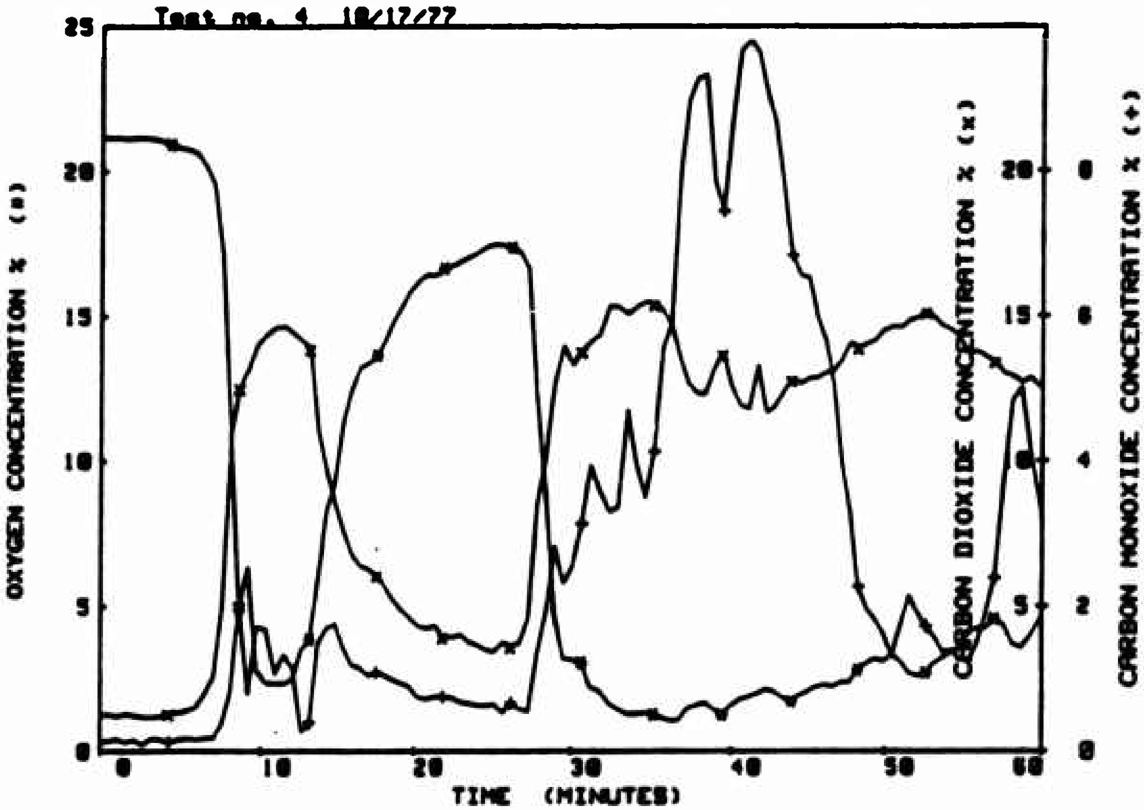


FIGURE 58. Inner Room Gas Concentration Histories for Burnout 4

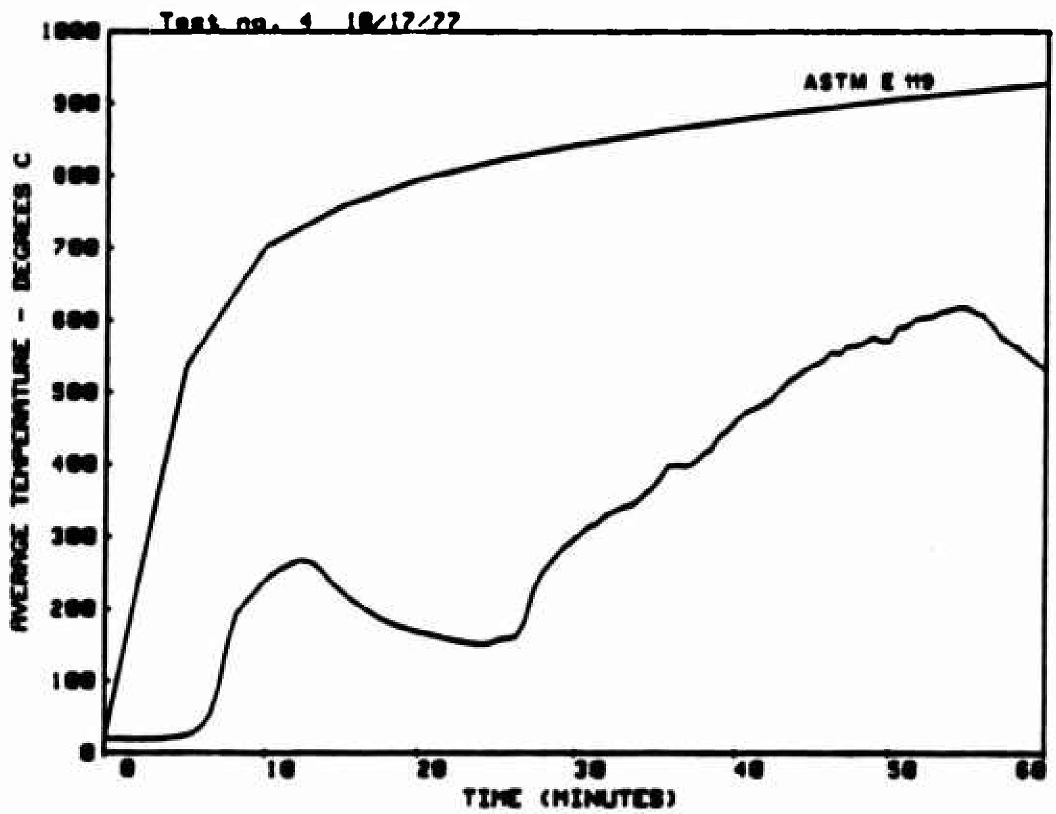


FIGURE 59. Average Doorway Temperature History for Burnout 4

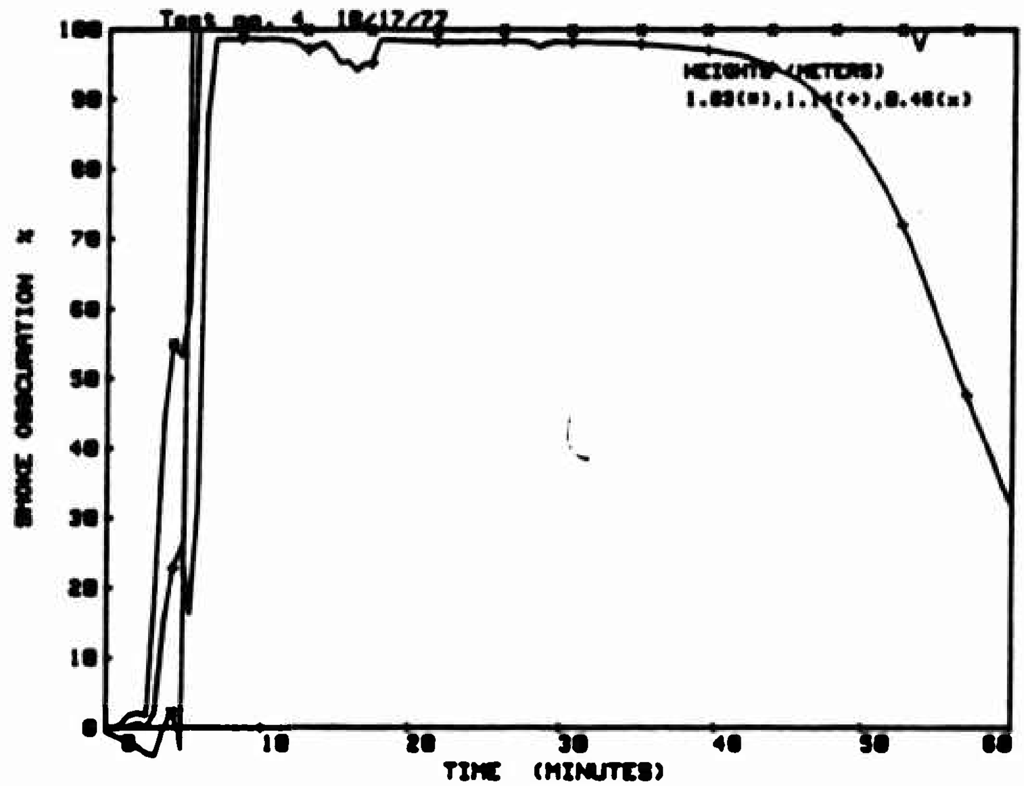


FIGURE 60. Smoke Obscuration Histories in Doorway for Burnout 4

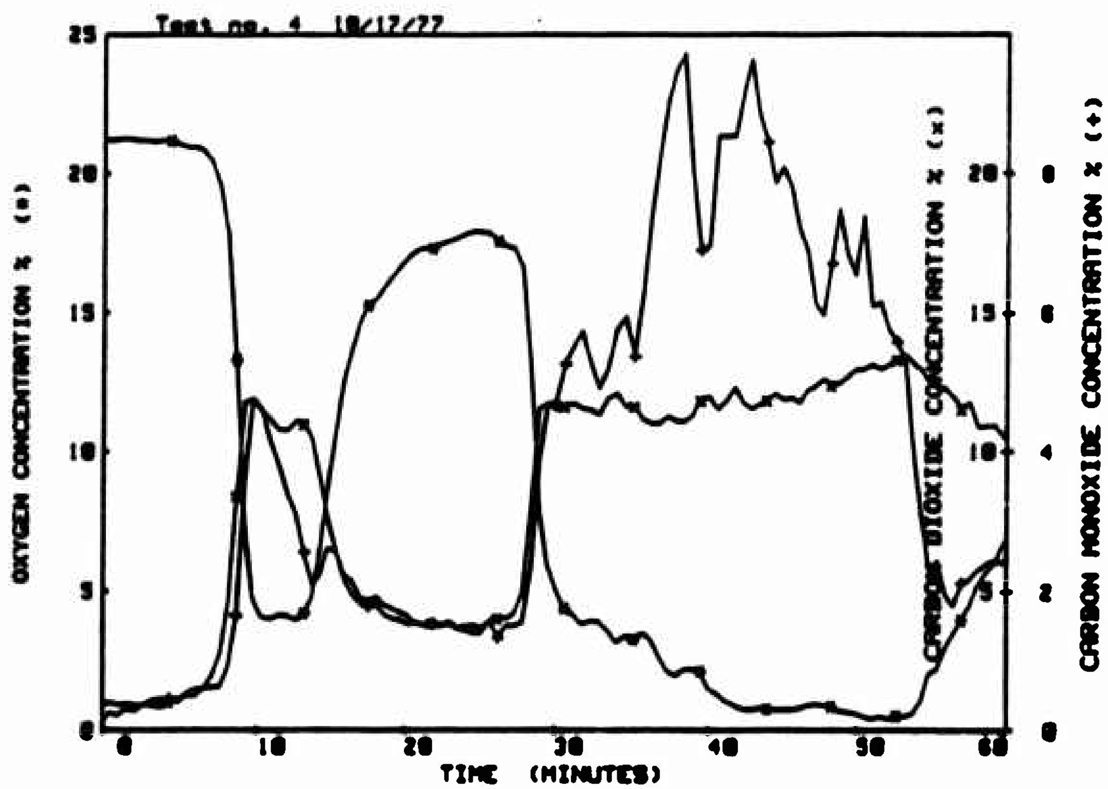


FIGURE 61. Doorway Gas Concentration Histories for Burnout 4

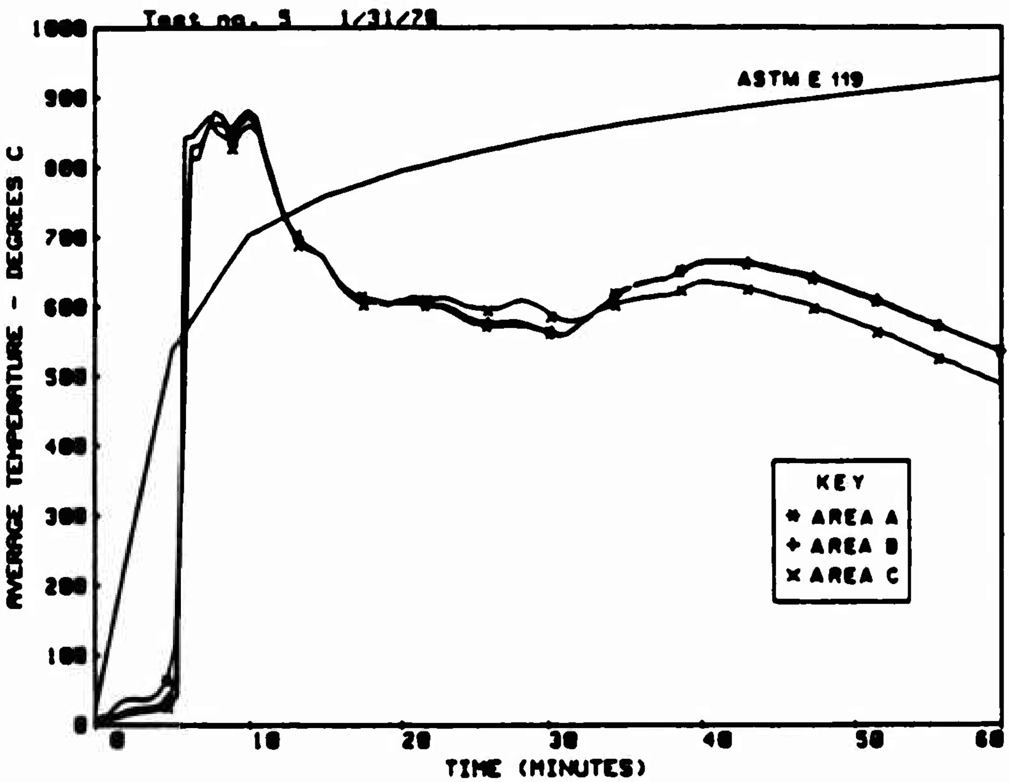


FIGURE 62. Average Upper (Level 1) Gas Temperature Histories for Burnout 5

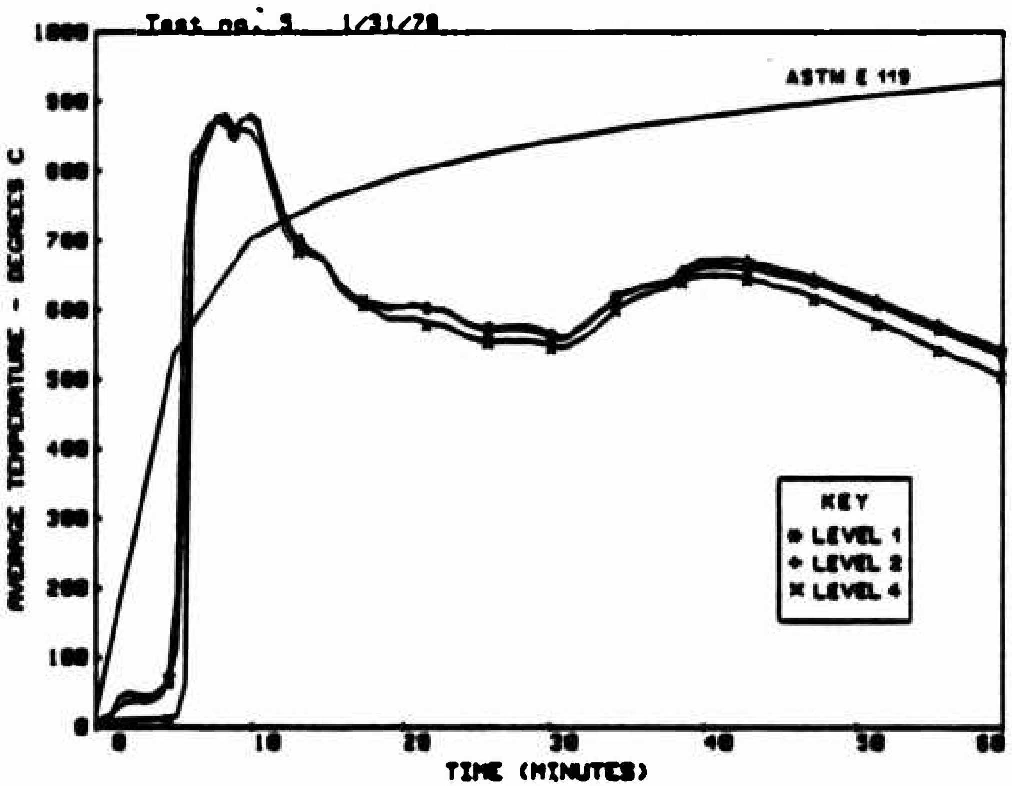


FIGURE 63. Average Inner Room (Area A) Gas Temperature Histories for Burnout 5

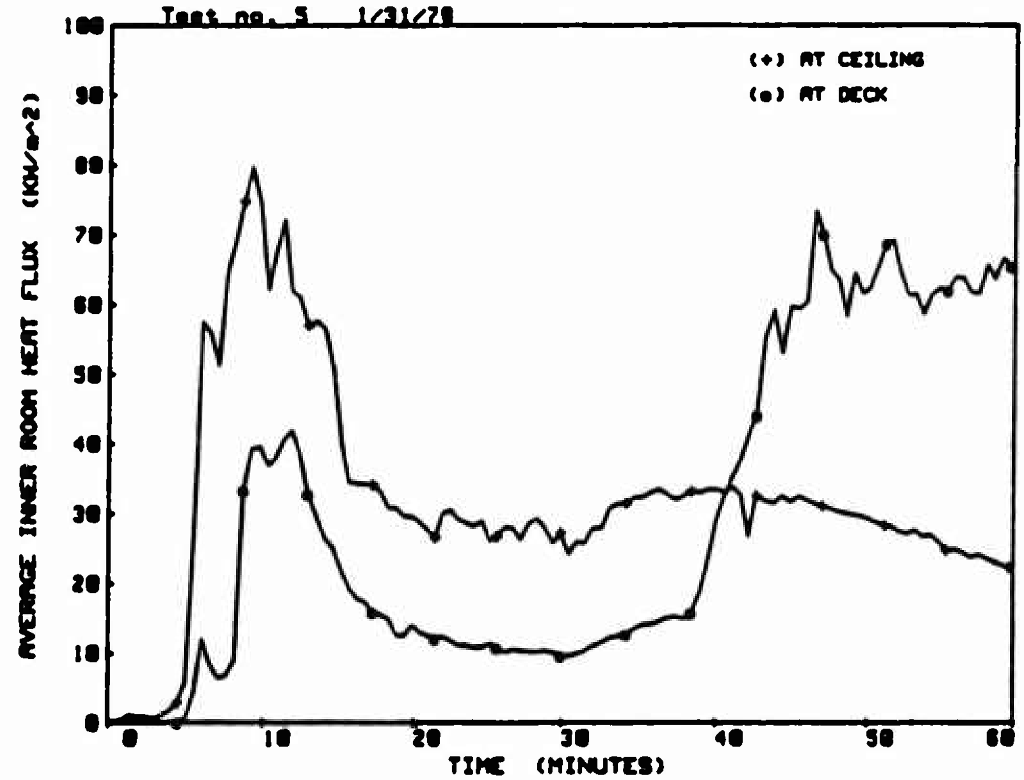


FIGURE 64. Average Inner Room Heat Flux Histories for Burnout 5

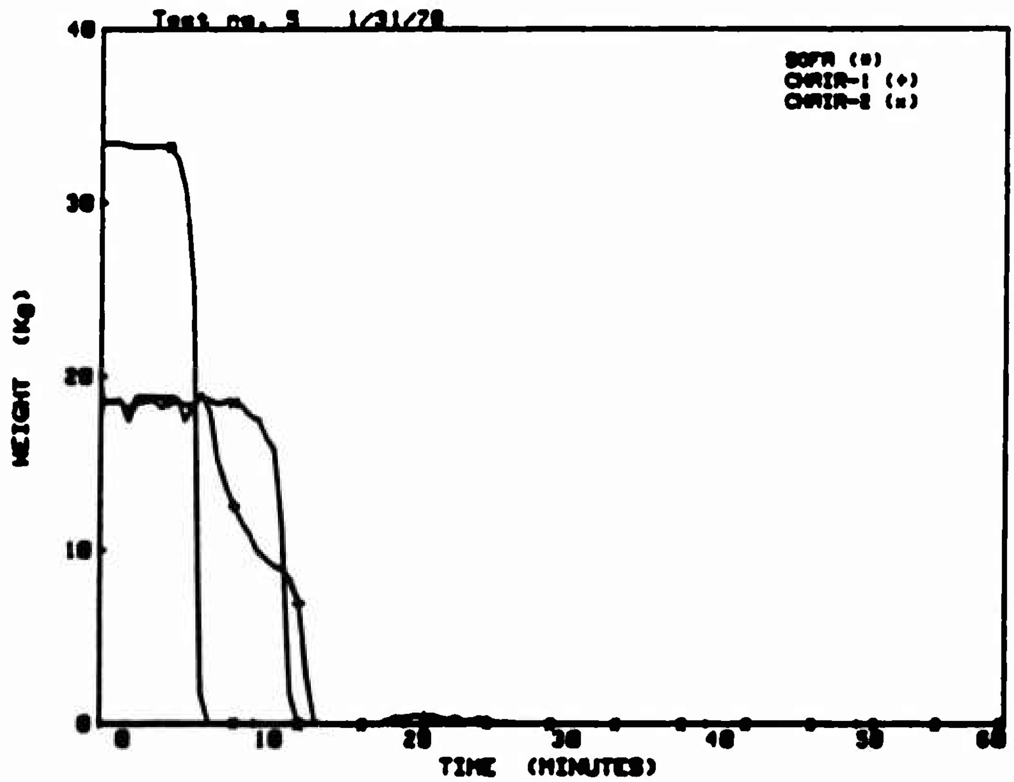


FIGURE 65. Weight Loss of Sofa and Chairs 1 and 2 for Burnout 5

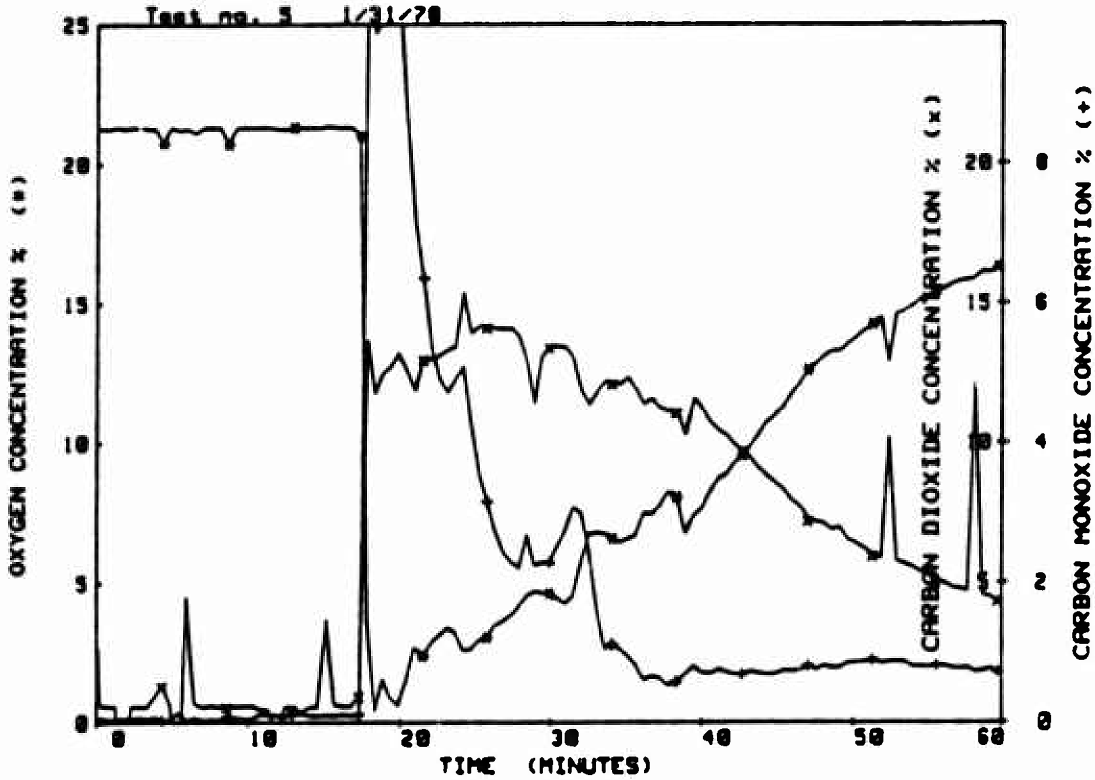


FIGURE 66. Inner Room Gas Concentration Histories for Burnout 5

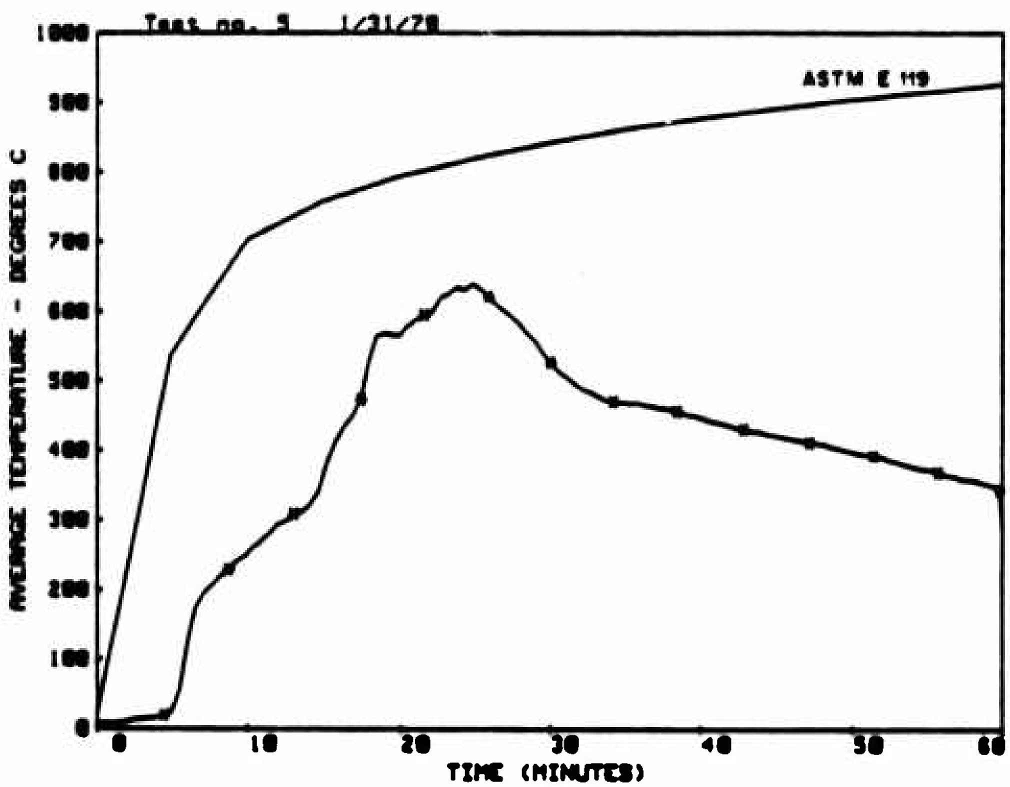


FIGURE 67. Average Doorway Temperature History for Burnout 5

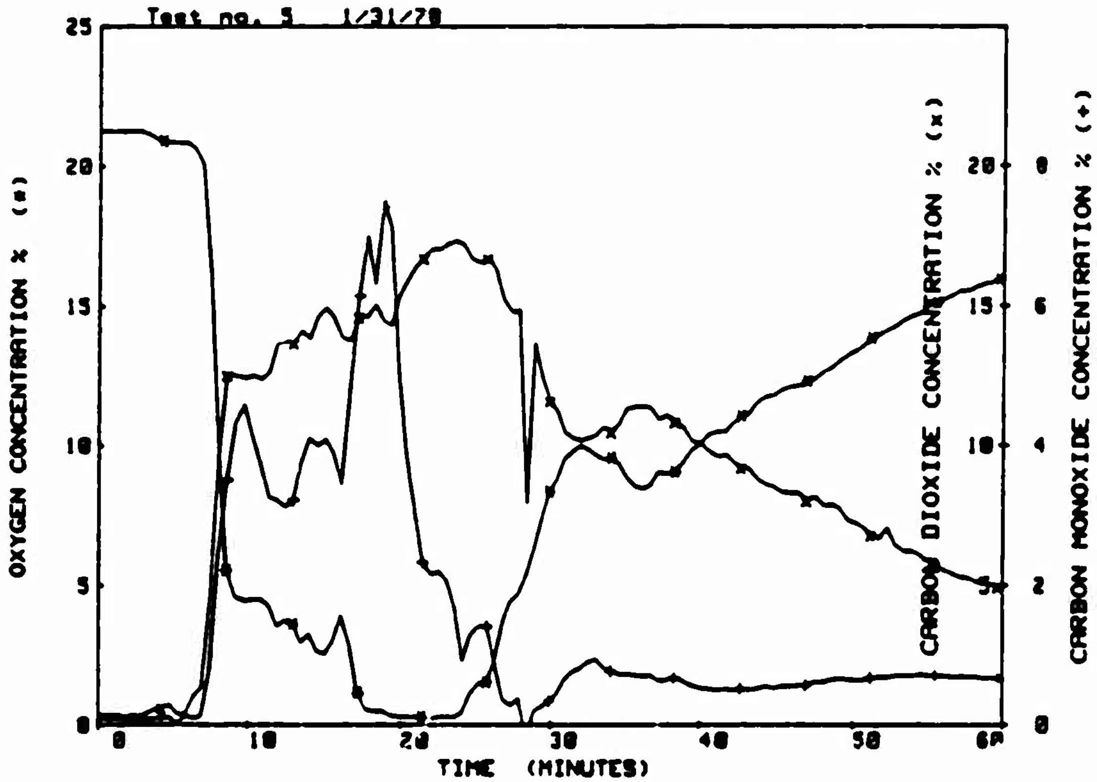


FIGURE 68. Smoke Obscuration Histories in Doorway for Burnout 5

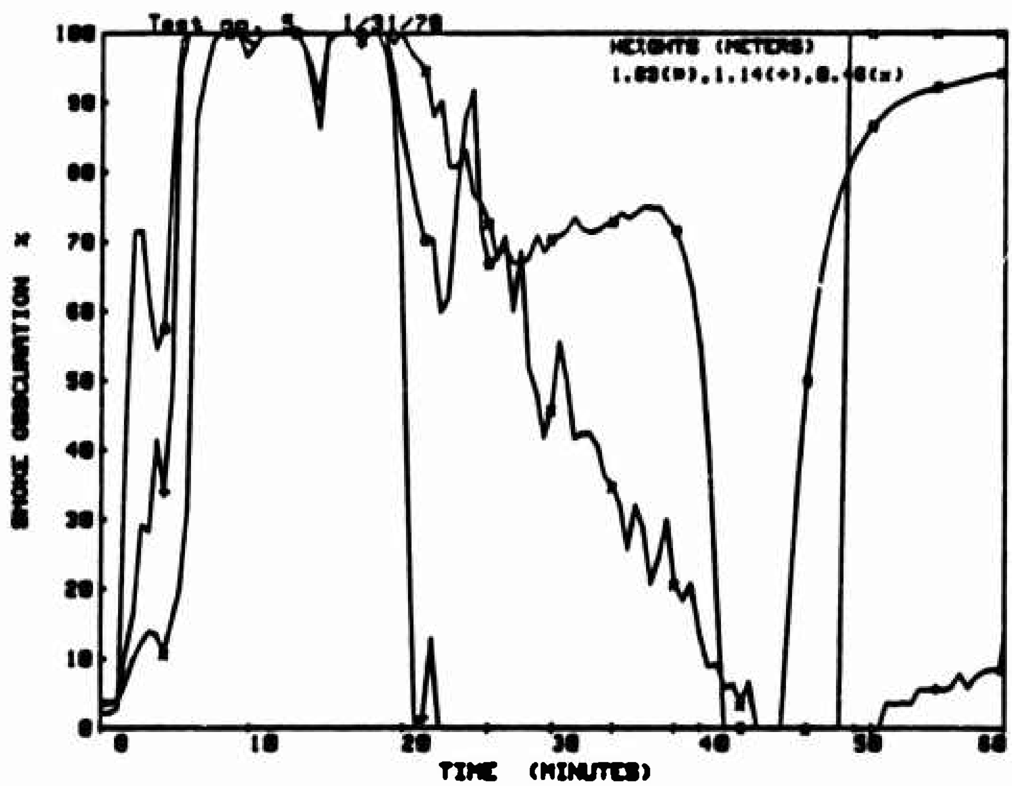


FIGURE 69. Doorway Gas Concentration Histories for Burnout 5

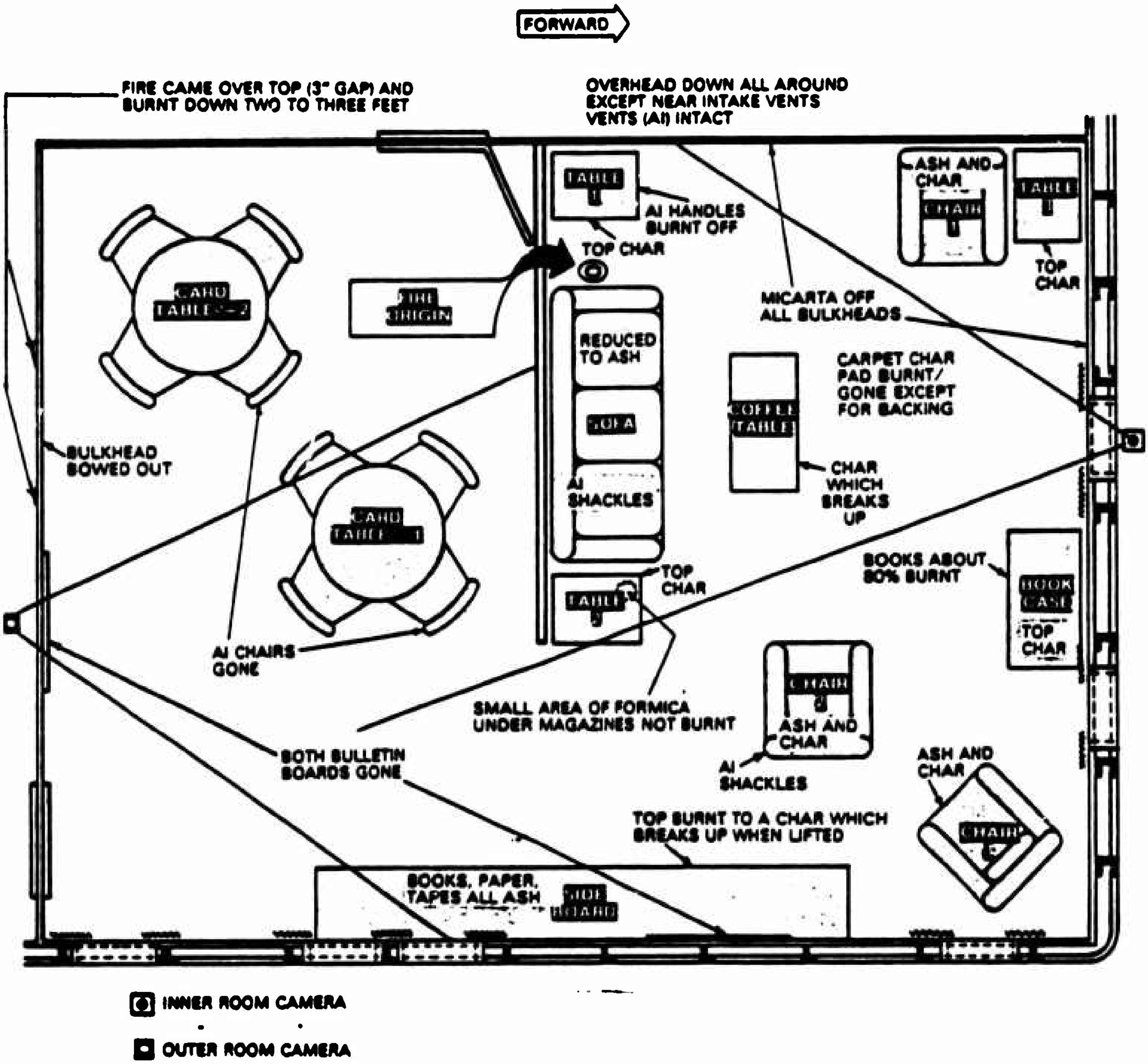


FIGURE 70. Extent of Damage for Burnout 4

TABLE 15

EXTENT OF FIRE DAMAGE FOR BURNOUT 4 (FORCED VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Shades and table top burnt to ash/char; lamp melted
Table & lamp 2	Shade burnt to ash - area under magazine not burnt
Table & lamp 3	Shades and table top burnt to ash/char; lamp melted
Chair 1	Totally burnt to ash
Chair 2	Totally burnt to ash
Chair 3	Totally burnt to ash
Coffee table	Top totally burnt to ash
Book case	Top, books on top and inside burnt to char
Sideboard	Top, books and miscellaneous burnt to ash
Carpet and pad	Totally burnt to ash
Curtains	Material not burnt - thread melted out
Wall covering	Came off in sheets and burned
Wall base	No effect
Tracking system	A few H posts warped and disengaged
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Totally consumed
Outer Room	
Card tables	Tops burnt to char - fell off
Steel chairs	All cushions burned - only steel frame left
Aluminum chairs	All cushions burned - aluminum melted
Bulletin boards	Burned and fell to deck
Carpet and pad	Totally burnt to ash
Wall covering	Came off in sheets and burnt
Wall base	No effect
Tracking system	H post warped and disengaged
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Totally consumed

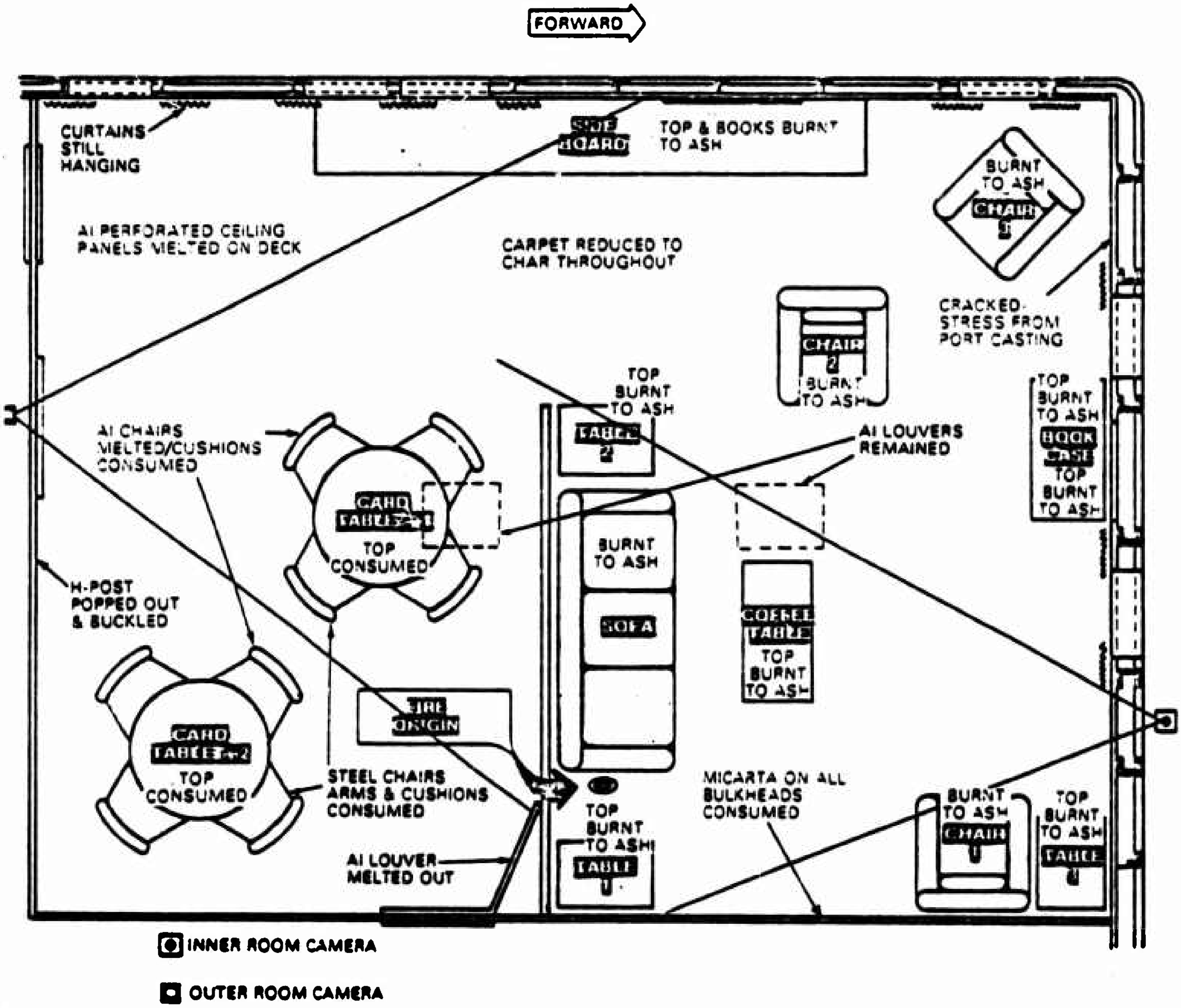


FIGURE 71. Extent of Damage for Burnout 5

TABLE 16

EXTENT OF FIRE DAMAGE FOR BURNOUT 5 (FORCED VENTILATION)

ITEM	DESCRIPTION OF DAMAGE
Inner Room	
Sofa	Totally burnt to ash
Table & lamp 1	Shades and table top burnt to ash/char - lamp melted
Table & lamp 2	Shades and table top burnt to ash/char - lamp melted
Table & lamp 3	Shades and table top burnt to ash/char - lamp melted
Chair 1	Totally burnt to ash
Chair 2	Totally burnt to ash
Chair 3	Totally burnt to ash
Coffee table	Top totally burnt to ash
Book case	Top, books on top and inside burnt to ash
Sideboard	Top, books and miscellaneous burnt to ash
Carpet and pad	Totally burnt to ash
Curtains	Material not burnt - thread melted out
Wall covering	Came off in sheets and burned
Wall base	No effect
Tracking system	H posts warped and disengaged
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Totally consumed
Outer Room	
Card tables	Tops burnt to char - fell off
Steel chairs	All cushions burned - only steel frame left
Aluminum chairs	All cushions burned - aluminum melted
Bulletin boards	Burned and fell off
Carpet and pad	Totally burnt to ash
Wall covering	Came off in sheets and burnt
Wall base	No effect
Tracking system	H posts warped and disengaged
Ceiling material	Melted and fell to deck
Light diffusers	Melted out
Combustibles	Totally consumed

4.4 Observations

All six of the lounge burnout fires exhibited a sort of "breathing." This was observed as smoke puffing from the lounge as the fire alternately intensified and died out. Oxygen concentration valleys and changes in the volumetric outflow and inflow rates in the doorway were observed. The temperature histories displayed discrete maximums in general correspondence with the oxygen depletion. Burnouts 1 and 2 exhibited three "breaths" corresponding to three temperature peaks for the upper gas temperatures in the inner room. Burnouts 3 through 6 on the other hand exhibited two "breaths" each with the second temperature peaks being of a much longer duration than the first. This phenomenon is believed to be caused by the ventilation limitations on the burnouts. As the fire begins, it produces large quantities of smoke and consumes oxygen at a very rapid rate. This reduces the oxygen level and tends to smother the fire. As the fire dies down, the amount of smoke and the oxygen consumption rate are reduced, thus allowing a buildup of the oxygen concentration and more radiation feedback to the combustibles. This results in an intensifying of the fire and the beginning of the second "breath." The minimal ventilation available during Burnouts 1 and 2 caused the process to repeat itself three times with fairly sharp temperature peaks. The increased ventilation afforded in Burnouts 3 through 6 probably permitted sufficient amounts of smoke to escape and oxygen to be drawn to the fire so that only 2 breaths were observed.

The fire buildup was observed to be relatively slow until the back of the sofa became engaged in the fire. When this occurred, the fire moved quite rapidly across the back of the sofa. This usually corresponded with the initial peak in the temperature histories and increased smoke production. The rapid flame spread was most likely due to a radiation feedback loop which was set up between the sofa back and the bulkhead some 8 to 12 inches behind it.

Flashover was not observed in any of the lounge burnouts as it was in the Cabin Burnouts and the Full-Scale Bedroom Fire Tests.[7] What was observed was an instantaneous involvement where an individual combustible such as a newspaper on the deck or a lampshade would burst into flames without any direct impingement of flame from another burning object. The principal difference between these burnouts and those where flashover was observed is ventilation. The Cabin Burnouts were conducted outside and the Full-Scale Bedroom Fire Tests were conducted in a building many times the size of the bedroom and liberally vented. Thus unlimited fresh air was available in these cases. It is believed that a room flashover did not occur in these burnouts because of the limited ventilation afforded in a ship's deckhouse. The principal means of escape of the fire gases from the lounge was through the doorway and into the area of the deckhouse which has limited volume. Once it became inundated, the gases, including the visible smoke, would back up into the lounge being burned. These gases would be cooler and thus serve to reduce the upper gas temperatures. This would in turn decrease the amount of radiation to the surrounding surfaces. The oxygen starvation, coupled with the back-up of the fire gases, eliminated the chance of a flashover.

The fire severity, determined as either the temperature-time product over the entire burnout or the maximum temperature observed during the burnout, was about equal for the burnouts with passive ventilation (Burnouts 3 and 6) and those with active ventilation (Burnouts 4 and 5), while the burnouts with closed ventilation (Burnouts 1 and 2) were much less severe. Before the tests it was hypothesized that the ceiling ventilation would permit a siphoning off of the hot gas layers in the upper portions of the lounge thereby removing the principal source of radiation to the combustibles. Thus it was expected that the forced ventilation case would produce the more severe fires, compared to the case of passive ventilation, since the former would provide more oxygen for the fire. The forced ventilation did not in actuality result in a decidedly more severe fire. This can be explained by the cooling of the room air, which effectively counteracted the assistance given to the fire by the greater oxygen supply.

The magnitude of the maximum temperatures observed in all of the burnout tests is suspect. They range from a low of 800°C in Burnouts 1 and 2 to a high of 890°C in Burnout 5. This suspicion was raised when some unpublished comparisons of thermocouple responses were made available by the National Bureau of Standards[9] (see figure 72). This work showed that after approximately ten minutes Inconel-sheathed thermocouples and fiberglass insulated thermocouples were indicating the same temperature, approximately 800°C. Over the next ten minutes, the Inconel-sheathed thermocouple rapidly proceeded to 1000°C and then further to a little over 1050°C while the fiberglass insulated thermocouples slowly rose to a maximum of just over 900°C. The explanation is that the binder in the fiberglass insu- lation carburizes in the 800 to 900°C range. This causes the thermocouple wires to short out which in effect moves the thermocouple junction to an area where the temperature is 800°C. While this problem seriously affects the precision of the temperature histories reported, they are still valuable as a minimum indication of the maximum temperatures in the fires. In other words, the fires were at least as hot as reported but could have been 100 to 200°C hotter.

It is interesting to compare these temperature histories with those from the State Room Fire Test and the Cabin Burnout Test reported on in section 1. The State Room Fire Test and these lounge burnouts are similar in that they both exhibit the "breathing" phenomenon discussed earlier in this section. The Cabin Burnout Test, on the other hand, does not exhibit a clear "breathing" phenomenon. Since the Cabin Burnout Test was conducted on a mockup with the cabin located on an outside fire ground, it did not have the same structural ventilation limitations that these lounge burnouts or the stateroom fire test had. Thus, the breathing phenomenon may be a result of the tight structures found on ships. These lounge burnouts reach much higher temperature peaks and the passive ventilation case sustained higher temperatures than witnessed in the State Room Fire Test. This is one indication that the modern materials and plastics used in the lounge burnouts produced a more rapid and constant heat release than the principally cellulosic materials used in the state room fire test. A comparison of the temperatures in these lounge burnouts and the cabin burnout test will not be made because the cabin burnout test was not ventilation-controlled.

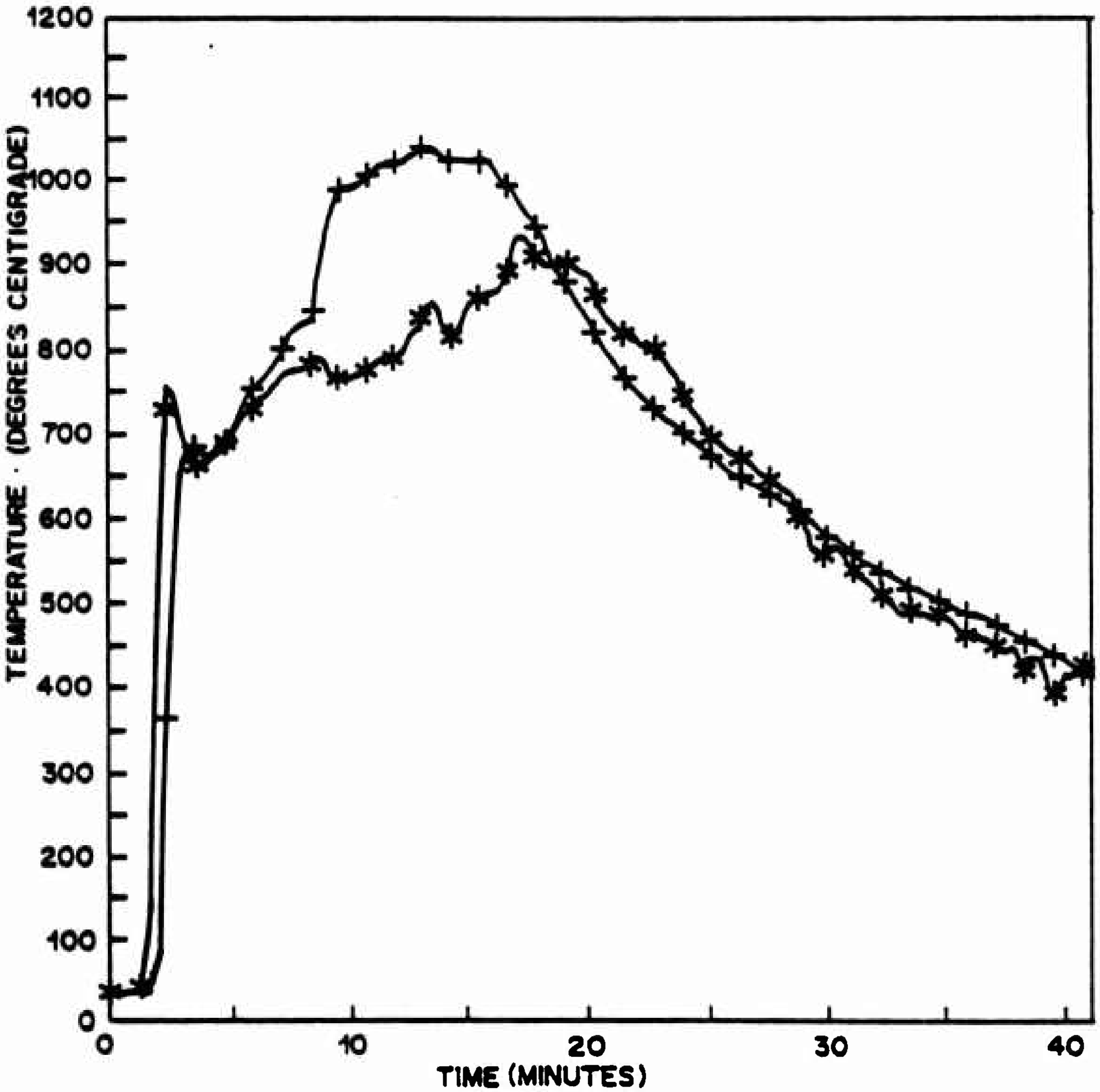


FIGURE 72. Comparison of Inconel Sheathed (+) and Fiberglass Insulated (*) Thermocouple Response

5.0 ANALYSIS AND DISCUSSION

The bulkhead panels of the test compartments consisted of a "non-combustible" substance manufactured by Johns Manville Corporation under the trade name Marinite. It was surfaced with a thin plastic veneer on either side. The non-combustible nature of the panel, except for the veneer which burns or peels off readily, was confirmed in the tests. In investigating how such a panel may fail during fire, the following possibilities were considered:

The panel fails by warping, thus providing a passage for the combustion products at its periphery, where it fits into a metal frame. This condition is heightened by differential thermal expansion between the two sides of the panel. The temperature difference, T, between the hot and the cold sides is an indicator of the severity of this condition. Thus, it was decided to compare T's imposed by the test fires with those imposed by the ASTM E119 fire.

The panel fails by disintegrating or crumbling. The severity of the fire necessary to produce this condition may be indicated by one or more of the following quantities:

a. The maximum temperature of the substance;
b. The heat flux entering the substance;
c. The energy absorbed by the substance.

It was decided to compare these quantities for the test fires with those for the ASTM E119 fire.

Some authors[10] have suggested that the measure of severity of a fire should be the heat flux-time product for the duration of a fire, in preference to the ASTM temperature-time profile or even the area under that profile (i.e., the temperature-time product). We will examine the severity of the test fires from these points of view also.

5.1 The Mathematical Model

The mathematical model for the panel exposed to fire is that of a one-dimensional plane wall of finite thickness and of infinite extent in directions perpendicular to that of the heat flow. It is known from previously published work[11] that radiant transfer from the fire to the wall is important. Since the actual fire may or may not be visible to the measuring point at the wall and also since it presents a varying, possibly small, view factor to the point, the assumption is made that the wall sees a black radiant gas whose temperature is continuously monitored. The sensor in the test series was a thermocouple, one inch away from the inside surface of the bulkhead. The following equations in conjunction with figure 73 describe this condition:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right), \quad 0 \leq x \leq L;$$

$$T(0,x) = T_a, \quad 0 \leq x \leq L: \text{ initial condition;}$$

$$\dot{q}_c = -k\left(\frac{\partial T}{\partial x}\right)_{x=0} = \sigma\epsilon\left\{T_g^4(t) - T^4(t,0)\right\} + h_i\left\{T_g(t) - T(t,0)\right\}$$

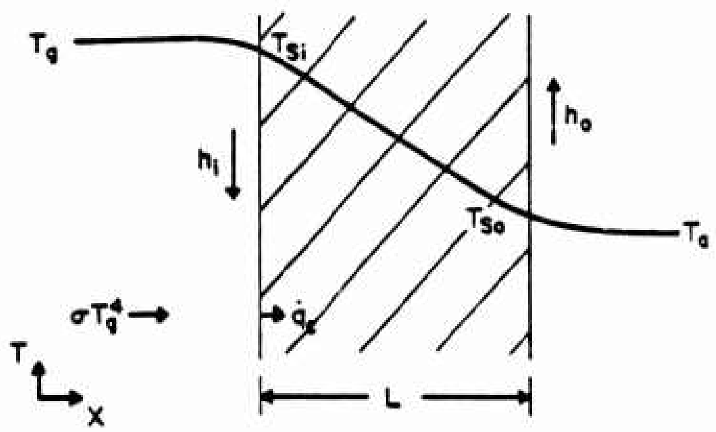


FIGURE 73. Schematic for Mathematical Model of Panel Exposed to Fire

for t 0: Hot boundary condition

$$-k\left(\frac{\partial T}{\partial x}\right)_{x=L} = \sigma\epsilon \left\{ T^4\ (t,L) - T_a{}^4 \right\} + h_o \left\{ T(t,L) - T_a \right\}$$

for t 0: Cold boundary condition

The symbols are:

T = temperature of the panel, K
t = time from ignition, sec
x = depth inside panel from hot surface, m
L = thickness of panel, m
T_g = hot gas temperature, K
T_a = ambient temperature, K
T_{si}, T_{so} = surface temperatures, inside and outside, K (see figure 73)
q_c = heat flux penetrating the panel, W/m^2
k = thermal conductivity of panel material, W/m K
h_i = convective heat transfer coefficient, hot side, W/m^2 K
h_o = convective heat transfer coefficient, cold side, W/m^2 K
= emissivity of the panel surface
= the Stefan-Boltzmann constant, 5.6726x10^{-8} W/m^{2}K^4
= density of the panel material, kg/m^3
= heat capacity of the panel material, J/kg K

The hot gas temperature for the ASTM E119 fire was approximated by the expression:

$$T_g - T_a = 580.0 \tanh (0.8429t) - 276.8 \tanh (0.9736\ t) + 714.4 \tanh (8.91\ t)$$

where T_g and T_a are both in degrees Kelvin and t is in hours, as adapted from Williams-Leir[12]. The hot gas temperatures for the test-fires were measured temperature-sequences, measured at scan-intervals ranging from 10 to 22 seconds.

The convective heat transfer coefficients, being very much affected by the turbulence induced in the compartment by release of the energy and the consequent rising temperature, were made a function of temperature as follows:

$$h = 12.6 + 0.04\ (T - 298)$$

where T is in degrees Kelvin and h is in W/m^{2}K.

The emissivity of both surfaces was assumed to be 0.9. The boundary conditions reflect heat transfer by both radiation and conduction. The thermal conductivity and heat capacity were made temperature-dependent, based on the manufacturers' data, as follows:

$$k(\mathrm{W/m\ K}) = 0.1139 + 1.46 \times 10^{-5}\ (T - 573);$$

$$c(\mathrm{J/kg\ K}) = 1046 + 0.628\ (T - 473),$$

where T is in degrees Kelvin.

The solutions, which are sets of temperature profiles, $T(t,x)$, through the thickness of the panel from face to face, can be obtained only by numerical methods. The physical properties for Marinite 36 are listed in table 17 while the difference equations used to solve the above equations can be found in appendix B. The results are summarized in table 18 and presented graphically in conjunction with the discussions in the next sections.

5.2 Analytical Results

Data from three of the burnouts (all with Marinite 36) have been used in the analysis: Burnout 1, where ventilation was provided by the doorway only; Burnout 3, in which passive (natural) ventilation was provided through roof vents and the doorway; and Burnout 5, which provided forced ventilation with the air-system blowing through the roof-vents and out the doorway. Burnouts 2, 6, and 4 were repeats of 1, 3, and 5, respectively, in which Marinite XL replaced Marinite 36. Reasonable reproducibility was observed for the repeats. The measuring point for gas-temperature input was a sensor location in each test, identified by data-channel 45 in Burnout 1, Ch. 70 in Burnout 3 and Ch. 70 in Burnout 5. These sensors were all located at the same spot, 1 inch off the inside surface of the side joiner bulkhead, 54 inches from the partition wall, and 10 inches above the floor. The sensors were about 4 feet from the origin of fire, which is nearer than most other parts of the compart- ment walls. The gas temperatures in the inner room, the room of fire-origin, were fairly uniform, varying only with height above the floor.

5.2.1 Hot Gas Temperatures

The temperature of the combustion products was seen to rise sharply (figure 74), exceeding the ASTM E119 profile within the first 5 to 15 minutes of ignition, depending on the ventilation mode. It dropped as sharply and thereafter was not seen to go above the ASTM E119 profile. This first flare-up is indicative of the beginnning of very vigorous burning of the sofa. The equally sharp drop is due to the reduction of oxygen in the compartment air. There is also a second and sometimes a third temperature-spike indicative of the deflagration spreading to new combustibles, chairs, etc., in the compartment and/or replenishment of oxygen in the compartment air.

There is a question regarding which point in a test-fire temperature-time curve to match with the ASTM E119 curve, since the test fires were always relatively slow to develop after ignition. The closed-ventilation case, Burnout 1, was the slowest and the forced ventilation case, Burnout 5, was the fastest. But no matter what adjustment is made, the maximum temperature in any of the 60-minute test fires is less than the temperature of the ASTM E119 profile at the sixtieth minute.

5.2.2 Heat Flux to the Bulkhead

Figure 75 shows the heat transferred to the bulkhead through 60 minutes of each test and compares it to that transferred during the hypothetical ASTM E119 fire. It is seen that the test fires all cause heat transfer rates for short durations that are many times what would be expected of the ASTM E119 fire. The peak heat fluxes to the bulkhead in all cases are of comparable magnitude. The bulkhead is seen to alternately absorb heat from and emit (both by radiation and conduction) heat to the hot gases. If heat

TABLE 17

PROPERTIES OF THE BULKHEAD PANEL (Marinite 36)

Density, nominal (dry):	36 lb/cu ft
Moisture content (normal):	5% dry weight
Modulus of rupture (flexural strength, dry):	1000 psi
Modulus of elasticity (from transverse test, dry):	0.36×10^6 psi

Temperature, $^{\circ}F$:	100	200	300	400	500	600	700	800	900	1000
Thermal conductivity, Btu/hr ft^2 $^{\circ}F$/in:	0.76	0.77	0.78	0.79	0.80	0.81	0.82	0.84	0.85	0.86

Temperature, $^{\circ}F$:	200	400	600	800
Specific heat, Btu/lb $^{\circ}F$	0.25	0.28	0.31	0.34

Panel thickness:	3/4-inch Marinite plus two 1/16-inch veneers
Panel size:	4 ft x 8 ft - cut to fit

TABLE 18

SUMMARY OF FIRE EFFECTS ON BULKHEAD PANEL

	TEST 1	TEST 3	TEST 5	ASTM E119
VENTILATION	CLOSED	PASSIVE	FORCED	
Maximum temperature, exposed side, °C at	773 15'53"	831 9'45"	869 9'37"	913 60'00"
Temperature-time integral, °C hr	184.7	586.8	585.4	762.0
Maximum heat flux entering wall, kW/m² at time	32.05 15'9"	21.63 8'4"	33.11 5'53"	7.50 5'40"
Heat flux-time integral, at 60 min, kWh/m²	1.04	0.78	0.90	2.60
Energy transfer, first spike, kWh/m²	0.52	0.88	1.22	-
Maximum energy absorbed, kWh/m² at time	0.60 16'30"	1.08 35'40"	1.27 12'30"	1.89 60'00"
Maximum temperature difference hot/cold-side, °C at time	748 16'00"	730 10'01"	638 9'57"	682 60'00"

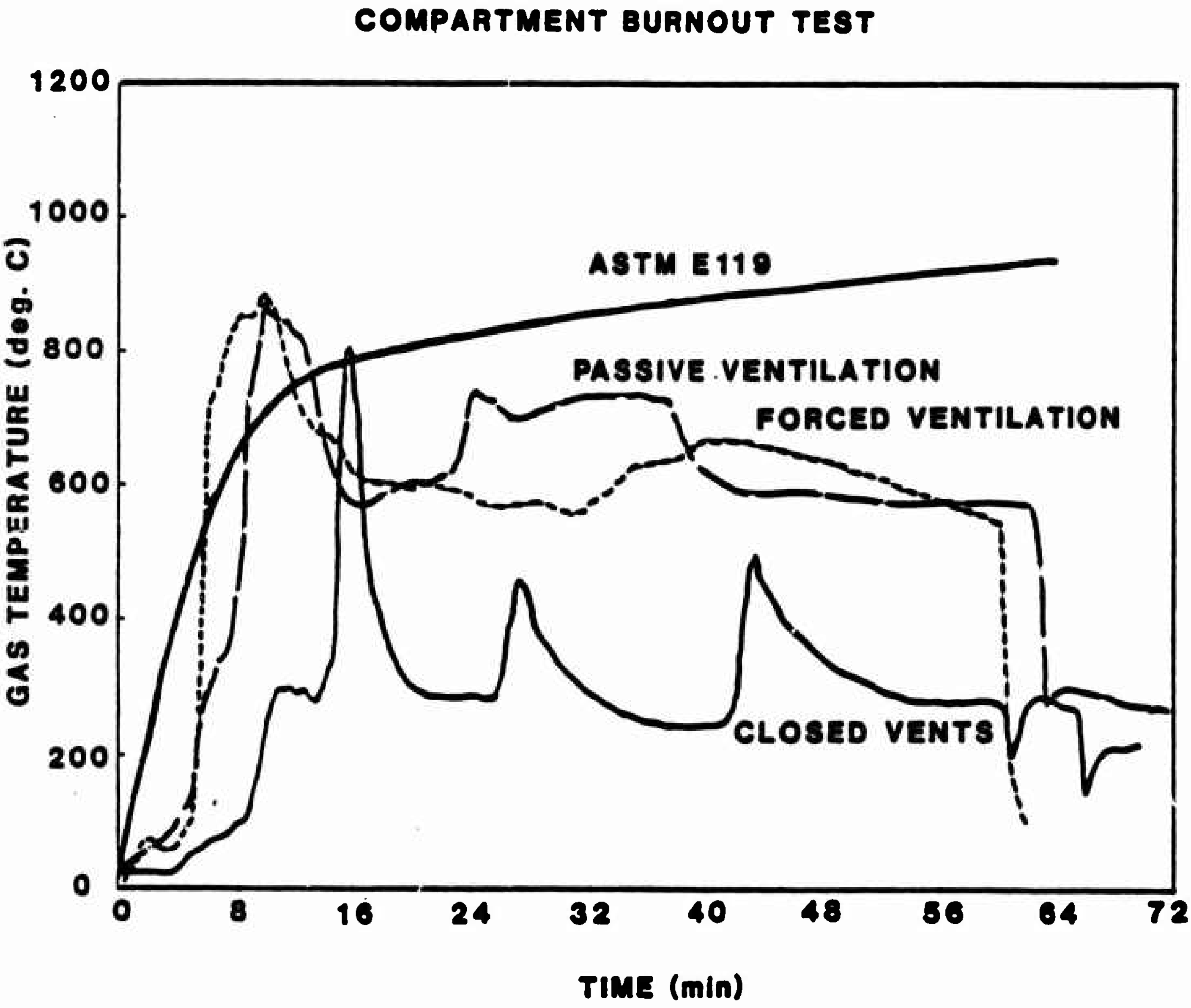


FIGURE 74. Gas Temperature Histories for Three Ventilation Cases

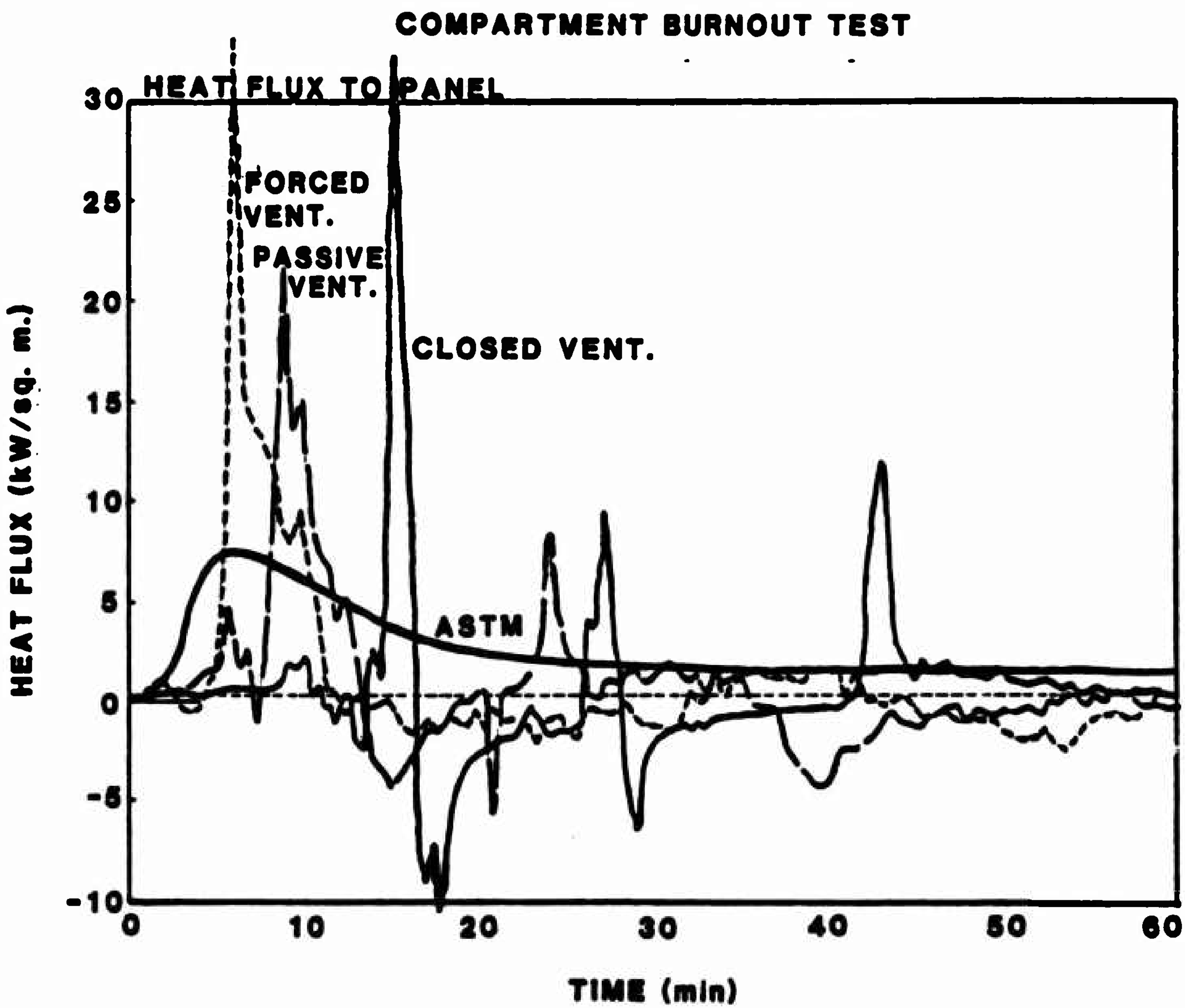


FIGURE 75. Calculated Heat Flux Histories Incident on a Panel

flux were the measure of fire severity, then the test fires, even though for short durations and several times during each test, were more severe than the ASTM E119 fire.

Significantly, the first heat flux peak comes earliest for the forced ventilation case and latest for the closed ventilation case. Also, in the three identical tests differing only by the mode of ventilation, there is only one peak for the forced ventilation case, two for passive ventilation and three for the closed-vents case. A study of the temperature curves (figure 74) and the heat flux curves (figure 75) suggests that forced fresh air ventilation keeps the fire going at a more uniformly intense burning rate than the other two modes of ventilation. Conversely, the more restricted the ventilation, the more frequent the occurrence of alternating intense fire and smouldering fire, referred to previously as "breathing."

5.2.3 Energy Absorption by the Bulkhead

Figure 76 shows the energy content of the bulkhead per unit surface area on one side as a function of time for each ventilation mode. The zero energy level is set in each case at the ambient temperature. It is seen that, within the first 15 minutes of Burnout 5, the forced ventilation case, the bulkhead has more energy than the ASTM E119 fire would have given it. Ultimately the ASTM E119 fire causes more energy absorption by this material. The maximum energy absorption by the bulkhead, ranked according to the mode of ventilation, is the highest for the forced ventilation case and lowest for the closed-ventilation case.

5.3 Discussion of Experimental and Analytical Results

5.3.1 Fire Severity

A significant result of this analysis is that the peak heat flux incident on the bulkhead in the actual test fires was found to exceed what a specimen would see in an ASTM E119 test. The highest heat flux occurs in the first flare-up. Even though the flux-time integral for the duration of any of the tests is relatively small compared to that for the ASTM E119 fire, the energy delivered in the first heat-flux "spike" is considerable. Table 18 shows that in one of the tests (the forced ventilation case) about 1.2 kWh/m^2 of surface area entered in 5 minutes. In another (the closed-ventilation case) about 0.5 kWh/m^2 entered in less than 3 minutes. According to the thermal ignition theory, combustible solids which are not overly reactive within the solid phase would ignite if sufficient heat flux is applied to their surface for a sufficiently long duration. At the level of heat flux produced by these tests, many other panel materials could have ignited. Marinite 36 did not.

By the hot-and-cold-side temperature differential criterion of fire severity, as experienced by the bulkhead material, the maximum value of T for these burnouts just exceeded the T due to an ASTM E119 fire momentarily (see figure 77). From this point of view, one would say that the test fires in the forced and the passive ventilation modes were about as severe as the ASTM E119 fire. The effect of this thermal shock is hard to assess. The existence of a temperature differential across a panel means that the two surfaces will expand at different rates. Some materials may be elastic

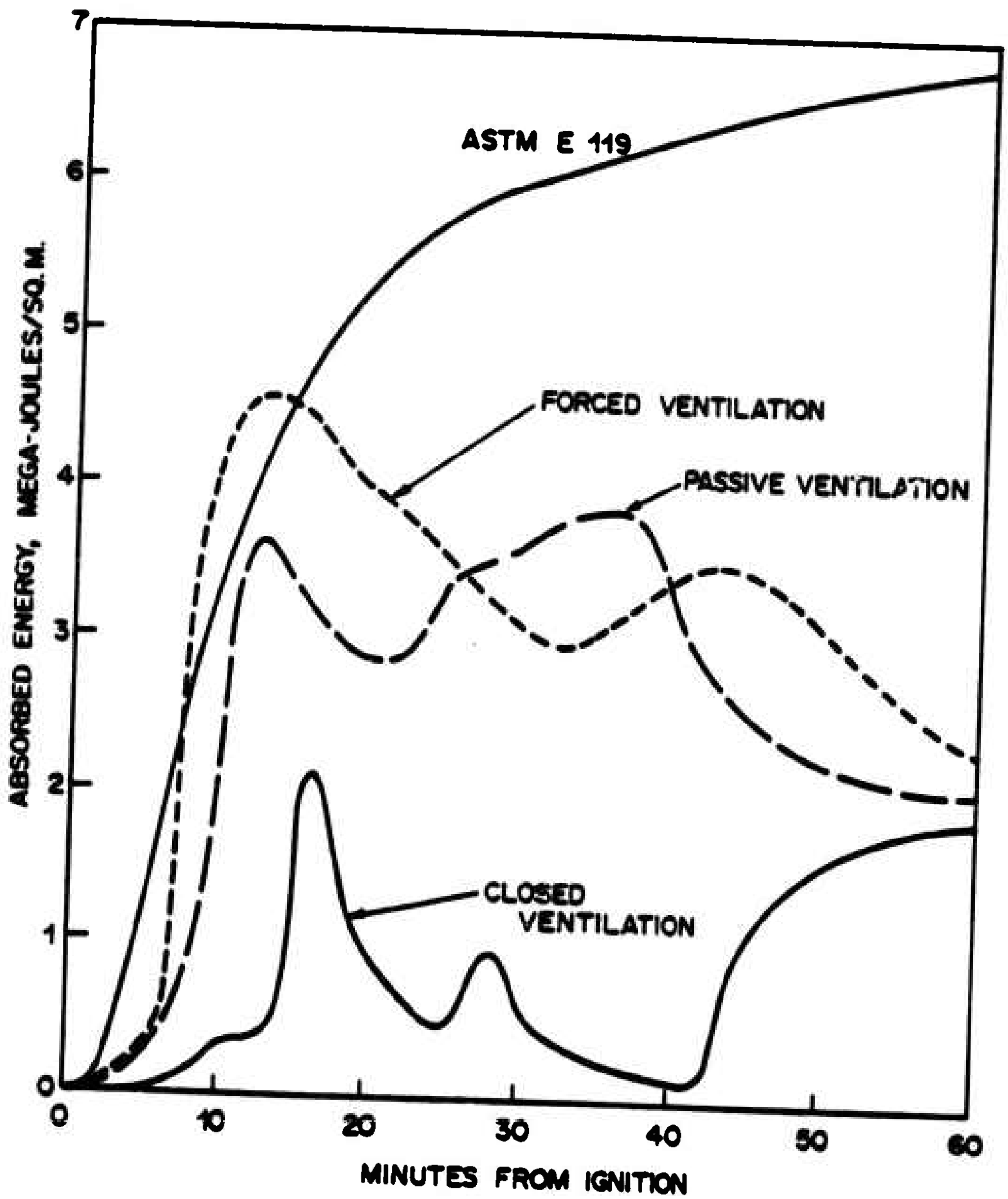


FIGURE 76. Calculated Absorbed Energy Histories for Bulkhead Panels

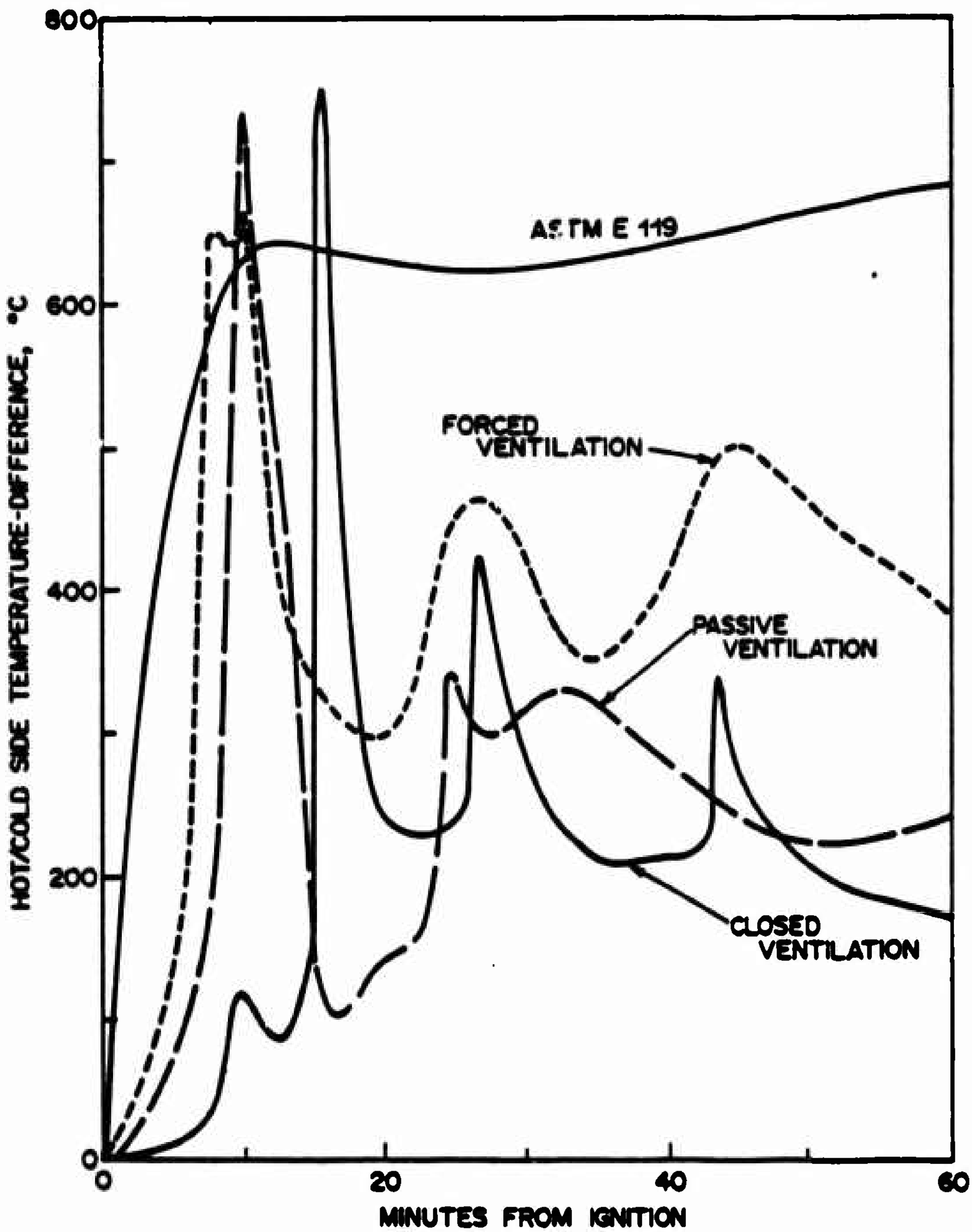


FIGURE 77. Hot and Cold Side Temperature-Differential Histories for Various Bulkhead Panel Exposures

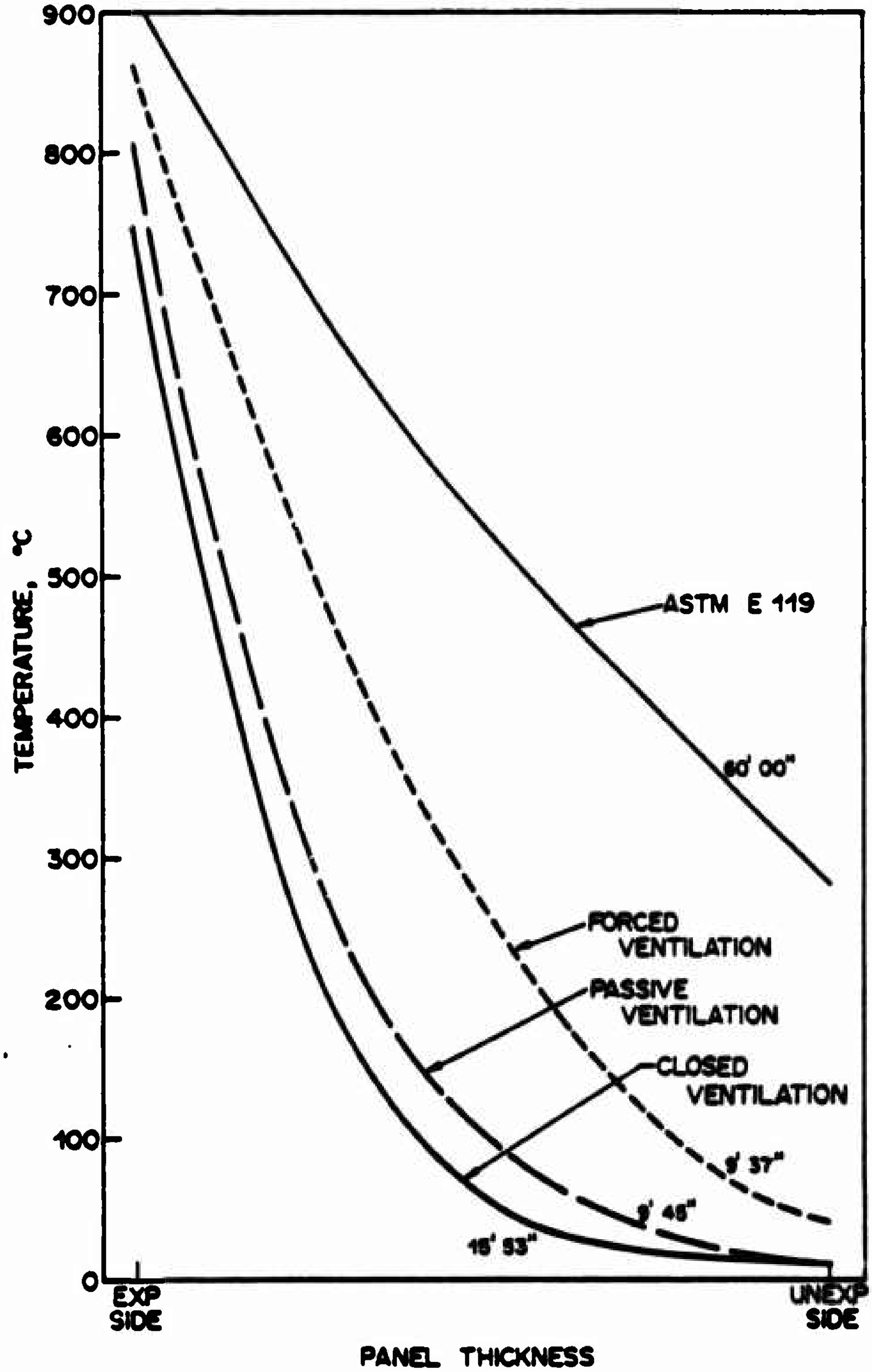


FIGURE 78. Temperature Profiles Through Panels at Maximum Exposed Side Temperatures

enough to withstand the resultant stress while other materials may fracture. By other criteria of fire severity, e.g., maximum temperature (figure 78), maximum energy absorption (figure 76), the temperature-time integral and the heat flux-time integral (Table 18), the test fires were less severe than the hypothetical ASTM E119 fire.

5.3.2 Behavior of Bulkhead Material

Marinite 36, the bulkhead material, stood the test well. It did not burn and did not crumble. No appreciable warping was noted, at least not enough to open up a passage for the hot gases at a junction. One panel did fall from its metal frame, but it was determined that the fit of the panel in the frame was responsible, rather than the panel itself. While the effects on Marinite XL have not been ana- lyzed in the same detail as those on Marinite 36, observations indicated that it also withstood the test fires.

5.3.3 The Effect of Ventilation

The test fires were all ventilation-controlled, as evidenced by the sharp temperature peaks which corresponded with the oxygen content of the air in the lounge sharply depleting after every spurt of combustion activity. This caused the temperature to fall. The effect of increasing ventilation clearly was to smooth out the fluctuations of temperature and heat flux through the compartment walls. The case of forced ventilation (Burnout 5), was the most effective in doing so. Ventilation hastened fire spread, as evidenced by the occurrence of the first "flare-up" (not flashover) occurring the soonest for the forced ventilation case, within 6 minutes of ignition, while in the closed ventilation case, it was delayed almost 12 minutes.

6.0 CONCLUSIONS

The principal result of this work is that the ASTM E119 fire test has been shown to provide a smaller factor of safety than it once did. The temperature histories observed for these burnouts in general did not exceed the temperature profile for the standard curve. They are, however, closer to the standard curve than temperature histories from the tests used to verify the standard curve for marine use in the past. This is inspite of the fact that the fuel load was 1/2 to 1/3 of that in the previous tests. Furthermore, the thermal buildup in the first 10 to 15 minutes is greater and resulted in temperatures which significantly exceed the standard curve during this period. Also the heat flux penetration into the bulkhead materials was higher for these burn- outs than for the ASTM E119 fire test over 60 minutes. These results were produced by a fuel load which was only about 60 percent of that in the NANTASKET burnouts. The materials now used produce more rapid and complete heat release.

This report discusses the burnouts in terms of their effect on the structural fire protection of ships. The more rapid thermal buildup observed also has a significant impact on life safety. It does not permit as much time to notify people to escape; smoke production will also be more rapid, thus making escape more difficult.

Another tentative result is that fires in ships compartments adjoining deck areas isolated from the environment do not appear to produce flashover. This is in contrast with fires in rooms in buildings which invariably flashover. The authors believe that the explanation for this difference centers around venti- lation. Ships provide an almost airtight enclosure which produces ventilation-controlled fires as discussed in section 4.4 and thus prevent flashover. On the other hand, windows in buildings often break, providing oxygen for the fire and permitting flashover.

A key observation during the tests was that the Marinite bulkhead panels contained the fires. Thus even though the fire seems more severe, the Marinite is still able to contain it. This could be in contrast to a material which marginally passed the ASTM E119 fire test. The few Marinite panels which did crack during the burnouts did not separate; thus they did not permit fire to pass the bulkhead. There were several cases where the tracking system released because of heat-induced distortions. This is not significant since they were not installed with screws as required by regulation. It is significant that the approved ceiling invariably fell out during a burnout. Thus the retention of structural fire boundaries requires the bulkheads to extend vertically from deck to deck.

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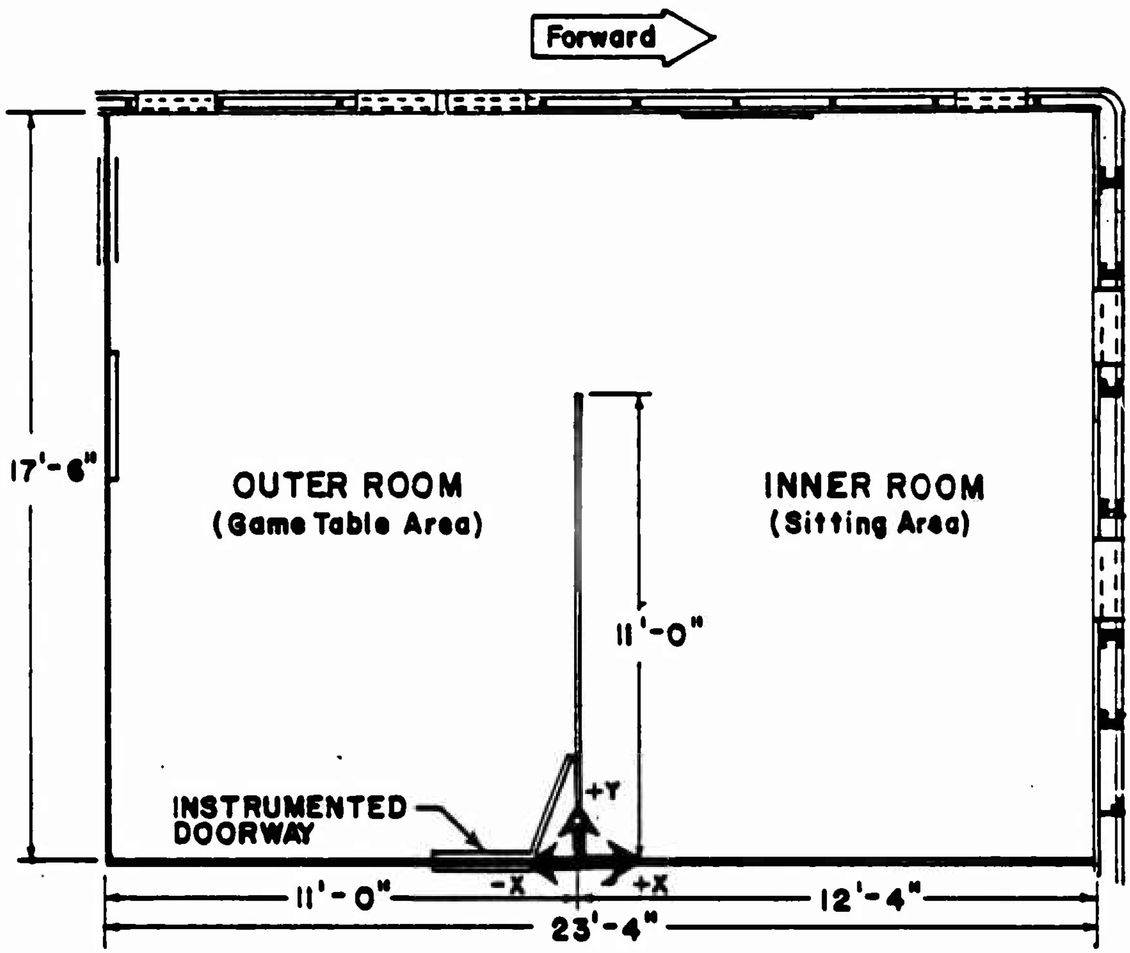
APPENDIX A

CHANNEL LISTINGS/TRANSDUCER LOCATIONS



Location System:

Coordinates X and Y are measured from the origin as shown and Z is measured down from the ceiling panels. The coordinates (X,Y,Z) are given in feet (') and inches (") unless otherwise noted.

TRANSDUCER LOCATIONS FOR LOUNGE BURNOUTS 1 AND 2

CHANNEL NUMBER	DESCRIPTIVE TITLE AND LOCATION
0	Smoke Density Meter: Doorway 72" High
1	Smoke Density Meter: Doorway 60" High
2	Smoke Density Meter: Doorway 45" High
3	Load Cell: Sofa
4	Load Cell: Chair 1
5	Load Cell: Chair 2
6	O_2 Concentration: Doorway 69" High
7	CO Concentration: Doorway 69" High
8	CO_2 Concentration: Doorway 69" High
9	O_2 Concentration: Inner Room (4'4", 3'5", 10")
10	CO Concentration: Inner Room (4'4", 3'5", 10")
11	CO_2 Concentration: Inner Room (4'4", 3'5", 10")
12	Calorimeter: Doorway 0" High
13	Calorimeter: Ceiling at Ignition Source (4', 4', 0")
14	Calorimeter: Ceiling at Ignition Source (6'6", 9', 0")
15	Calorimeter: Deck of Inner Room (6'6", 9', On Deck)
16	Radiometer: Deck of Inner Room (6'6", 9', On Deck)
17	Calorimeter: Deck of Outer Room (-8', 7', On Deck)
18	Radiometer: Deck of Outer Room (-8', 7', On Deck)
19	Compartment Pressure (6'6", 9', Deck)
20	Ceiling T/C (-8', 7', 3")
21	Ceiling T/C (-2', 5', 3")
22	Ceiling T/C (1', 10', 3")
23	Ceiling T/C (6'6", 9', 3")
24	Ceiling T/C (6', 3', 3")
25	Ceiling T/C (10', 2', 3")
26	T/C String 1 (4'4", 3'5", Above Panel)
27	T/C String 1 (4'4", 3'5", 3")
28	T/C String 1: Air Aspirated (4'4", 3'5", 3")
29	T/C String 1 (4'4", 3'5", 10")
30	T/C String 1: Air Aspirated (4'4", 3'5", 10")
31	T/C String 1 (4'4", 3'5", 3'6")
32	T/C String 2 (1', 14', Above Panel)
33	T/C String 2 (1', 14', 3")
34	T/C String 2 (1', 14', 10")
35	T/C String 2 (1', 14', 3'6")
36	Forward Weather Bulkhead T/C (1" Off, 9', 12")
37	Forward Weather Bulkhead T/C (Back Surface, 9', 12")
38	Forward Weather Bulkhead T/C (Steel Surface, 9', 12")
39	Forward Weather Bulkhead T/C (1" Off, 10', 24")
40	Forward Weather Bulkhead T/C (1" Off, 3', 9")
41	Side Weather Bulkhead T/C (6', 1" Off, 12")
42	Side Weather Bulkhead T/C (6', Back Surface, 12")
43	Side Weather Bulkhead T/C (6', Steel Surface, 12")
44	Side Weather Bulkhead T/C (1'6", 1" Off, 8")
45	Side Joiner Bulkhead T/C (3'9", 1" Off, 10")
46	Side Joiner Bulkhead T/C (3'9", Back Surface, 10")

TRANSDUCER LOCATIONS FOR LOUNGE BURNOUTS 3, 4, 5, AND 6

CHANNEL NUMBER	DESCRIPTIVE TITLE AND LOCATION
0	Smoke Density Meter: Doorway 72" High
1	Smoke Density Meter: Doorway 45" High
2	Smoke Density Meter: Doorway 18" High
3	Load Cell: Sofa
4	Load Cell: Lounge Chair 1
5	Load Cell: Lounge Chair 2
6	O_2 Concentration: Doorway 68" High
7	CO Concentration: Doorway 68" High
8	CO_2 Concentration: Doorway 68" High
9	O_2 Concentration: Inner Room (5', 3', 10")
10	CO Concentration: Inner Room (5', 3', 10")
11	CO_2 Concentration: Inner Room (5', 3', 10")
12	O_2 Concentration: Inner Room (6.5', 9', 60")
13	Calorimeter: Ceiling (5', 3', 0)
14	Calorimeter: Ceiling (6.5', 9', 0)
15	Calorimeter: Deck of Inner Room (6.5', 9', 81")
16	Radiometer: Deck of Inner Room (6.5', 9', 81")
17	Radiometer: Deck of Outer Room (-8', 8', 81")
18	Calorimeter: Bulkhead (6', 0, 18")
19	Radiometer: Bulkhead (6', 0, 18")
20	Doorway T/C 75" High
21	Doorway T/C 68" High
22	Doorway T/C (Air Aspirated) 68" High
23	Doorway T/C 56" High
24	Doorway T/C 44" High
25	Doorway T/C (Air Aspirated) 44" High
26	Doorway T/C 32" High
27	Doorway T/C 20" High
28	Doorway T/C 8" High
29	Ventilation Duct T/C
30	Doorway Air Flow Probe 75" High
31	Doorway Air Flow Probe 68" High
32	Doorway Air Flow Probe 56" High
33	Doorway Air Flow Probe 44" High
34	Doorway Air Flow Probe 32" High
35	Doorway Air Flow Probe 20" High
36	Doorway Air Flow Probe 8" High
37	Doorway Air Flow Probe: Ventilation Duct
38	- OPEN -
39	- OPEN -
40	T/C String 1 (5', 3', 1" Above Panel)
41	T/C String 1 (Air Aspirated) (5', 3', 1" Above Panel)
42	T/C String 1 (5', 3', 3")
43	T/C String 1 (Air Aspirated) (5', 3', 3")
44	T/C String 1 (5', 3', 12")
45	T/C String 1 (5', 3', 3')
46	T/C String 1 (5', 3', 1" Above Deck)

CHANNEL NUMBER	DESCRIPTIVE TITLE AND LOCATION
47	Side Joiner Bulkhead T/C (-9', 1" Off, 16")
48	Aft Joiner Bulkhead T/C (1" Off, 13', 15")
49	Aft Joiner Bulkhead T/C (Back Surface, 13', 15")
50	Partition-Inner Room (1" Off, 6', 12")
51	Partition-Outer Room (Back Surface, 6', 12")
52	Doorway T/C 75" High
53	Doorway T/C 69" High
54	Doorway T/C (Air Aspirated) 69" High
55	Doorway T/C 57" High
56	Doorway T/C 42" High
57	Doorway T/C (Air Aspirated) 42" High
58	Doorway T/C 27" High
59	Deck T/C (6'6", 9', 1" Off Deck)

CHANNEL NUMBER	DESCRIPTIVE TITLE AND LOCATION
47	T/C String 1 (Air Aspirated) (5', 3', 1" Above Deck)
48	Ceiling T/C (10', 2', 3")
49	Ceiling T/C (8', 5', 0)
50	Ceiling T/C (6.5', 9', 0)
51	Deck T/C (6.5', 9', 1" Above Deck)
52	Ceiling T/C (1', 10', 0)
53	T/C String 2 (8', 14', 3")
54	T/C String 2 (8', 14', 12")
55	T/C String 2 (8', 14', 5")
56	T/C String 3 (1', 14', 1" Above Panel)
57	T/C String 3 (1', 14', 3")
58	T/C String 3 (1', 14', 12")
59	T/C String 3 (1', 14', 3")
60	T/C String 3 (1', 14', 5")
61	T/C String 3 (1', 14', 1" Above Deck)
62	Ceiling T/C (-7', 14', 0)
63	T/C String 4 (-8', 8', 1" Above Panel)
64	T/C String 4 (-8', 8', 3")
65	T/C String 4 (-8', 8', 12")
66	T/C String 4 (-8', 8', 5')
67	Ceiling T/C (-2', 4', 0)
68	Partition T/C (1" Off, 6', 12")
69	Partition T/C (Surface, 6', 12")
70	Side Joiner Bulkhead (54", 1" Off, 10")
71	Side Joiner Bulkhead T/C (54", Back Surface, 10")
72	Side Joiner Bulkhead T/C (7', 1" Off, 18")
73	Side Joiner Bulkhead T/C (7', Back Surface, 18")
74	Forward Weather Bulkhead T/C (1" Off, 3', 9")
75	Forward Weather Bulkhead T/C (1" Off, 9', 12")
76	Forward Weather Bulkhead T/C (Back Surface, 9', 12")
77	Forward Weather Bulkhead T/C (Steel Surface, 9', 12")
78	Forward Weather Bulkhead T/C (1" Off, 10', 24")
79	Forward Weather Bulkhead T/C (1" Off, 15', 10")
80	Side Weather Bulkhead T/C (7', 1" Off, 12")
81	Side Weather Bulkhead T/C (7', Back Surface, 12")
82	Side Weather Bulkhead T/C (7', Steel Surface, 12")
83	Side Weather Bulkhead (2', 1" Off, 8")
84	Aft Joiner Bulkhead T/C (1" Off, 13', 15")
85	Aft Joiner Bulkhead T/C (Back Surface, 13', 15")
86	Side Joiner Bulkhead T/C (-9', 1" Off, 16")
87	Partition T/C (1" Off, 5', 12")
88	Doorway T/C: Air Aspirated (20", 12")

APPENDIX B
DIFFERENCE EQUATIONS

Finite difference integration techniques were used in the numerical solution of the differential equation in Section 5.1. The difference equations used are as follows. The symbols are the same. The subscripts i and j represent time (t) and depth (x) respectively. The intervals are represented by Δt and Δx:

$$T_{i+1,j} = T_{i,j} + \alpha \frac{\Delta t}{2\Delta x^2} (T_{i,j-1} - T_{i,j} - T_{i,j+1} + T_{i,j+2}),$$
$$i=1,2 \cdots; \quad j=2,3,\cdots 100$$

$$T_{i+1,1} = T_{i+1,3} - 2\,\Delta x \left(\frac{dT}{dx}\right)_{i+1}, \quad i=1,2,\cdots$$

$$\text{where } \left(\frac{dT}{dx}\right)_{i+1} = \frac{1}{k} [\sigma\varepsilon\{(T_{g_{i+1}}, + 273.15)^4 - (T^o_{i+1,1} + 273.15)^4\}$$
$$+ h_i(T_{g_{i+1}} - T^o_{i+1,1})]\text{: hot boundary condition}$$

$$\text{and } T^o_{i+1,1} = T_{i,1} + T_{g_{i+1}} - T_{g_i}$$

$$T_{i,j} = T_a, \; j=1,2,\cdots 102\text{: initial condition}$$

$$T_{i+1,102} - T_{i+1,100} - 2\frac{\Delta x}{k} [\sigma\varepsilon\{(T_{i+1,100} + 273.15)^4$$
$$-(T_a + 273.15)^4\} + h_o(T_{i+1,100} - T_a)]\text{: cold boundary condition}$$

$$T_{i+1,101} = \frac{2}{3}(T_{i+1,102} + \frac{3}{2} T_{i+1,100} + \frac{1}{2} T_{i+1,99} - \frac{1}{2} T_{i+1,98})$$

The above algorithm enables computation for any length of test duration which, in this case, was 3600 seconds.